PROGRESS REPORT 4

THE MEASUREMENT OF MOISTURE GRADIENTS IN CONCRETE PAVEMENT SLABS

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by

J. R. BELL

Joint Highway Research Project

PURDUE UNIVERSITY
LAFAYETTE INDIANA

Progress Report No. 4

THE MEASUREMENT OF MOISTURE GRADIENTS IN CONCRETE PAVEMENT SLABS

TO: K. B. Woods, Director
Joint Highway Research Project

September 5, 1962

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

File: 9-7-3
Project: C-36-63C

Progress Report No. 4 on the HPS research project entitled "The Measurement of Moisture Gradients in Concrete Pavement Slabs" is attached. This report has been authored by Mr. J. R. Bell, Research Engineer on our staff, and the research has been performed under the direction of Dr. G. A. Leonards. Mr. Bell also utilized the research for a thesis in partial fulfillment of the requirements for the Ph.D. degree.

Active research on this project terminated with the completion of this Progress Report No. 4. Activity between now and December 31, 1962, will be utilized to prepare a final summary report of the activity on this project from its inception until the present date. After that final report has been reviewed and finally approved by all parties concerned with the research, this study will be terminated.

The report is presented to the Board as information. Review of the report and comments on it would be appreciated.

Respectfully submitted,

Harold L. Michael

Harold L. Michael, Secretary

HLM:kmc

Attachment

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PROGRESS REPORT NO. 4

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by

J. R. Bell
Research Engineer

Joint Highway Research Project
File No: 9-7-3
Project No: C-36-63C

Purdue University
Lafayette, Indiana

September 5, 1962

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Special acknowledgment is due Dr. G. A. Leonards, Professor of Soil Mechanics, Purdue University, who guided this study and whose critical review of the manuscript was most helpful.

Many individuals contributed to this project and to each of these the author expresses his deepest appreciation. He is especially grateful to Mr. J. M. Mlynarik who prepared the computer programs and assisted with the electrical equipment designs.

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ABSTRACT

The dielectric properties of one concrete and one mortar mix were measured by laboratory tests. The equipment and procedures employed in these tests were selected to be adaptable to field measurements should they be proved feasible. The relative dielectric constant and dielectric conductivity-water content relationships were determined from permittivity measurements conducted at 10^6 cps by the AC bridge method. The dielectric conductivity relationship was also obtained from 10 cps resistance measurements. The samples were tested through ten cycles of drying and rewetting with distilled water. One half of the samples were cycled by drying to 105°C; the remainder were dried to only 60°C. Additional tests were conducted on selected samples to investigate the influence of increasing the salt content of the pore water.

The results of this investigation show that the relationships between the dielectric properties of concrete and water content are not constant. They are strongly influenced by many factors other than water content, including electrical frequency of the measurements, salt content of the pore fluid, ambient temperature and humidity, maximum drying temperature to which the concrete is subjected, and size of the test specimens. The results also show that large changes in these relationships result only from the extreme conditions of drying very thin samples to 105°C or from the samples being soaked in a concentrated NaCl solution. For thicker specimens dried to only 60°C and

subjected to ten cycles of drying and rewetting with distilled water without the addition of salts, the relationships between the dielectric properties and water content exhibited only minor variations.

It is concluded that the dielectric properties are capable of serving as accurate moisture indicators for many applications where extreme environmental conditions do not prevail and where large quantities of salts are not added to the pore water during the period of the test. Corrections are necessary if the dry weight of the concrete increases significantly with aging.

For moderate environmental conditions, the dielectric properties of concrete as determined from permittivity measurements are potentially capable of indicating the water content of hardened concrete with an accuracy of $\pm 0.25\%$ for moisture contents up to 6 to 8%. Low frequency resistance measurements have an indicated accuracy only half that of the permittivity test, but there are indications that this accuracy could be improved. Because of its relative simplicity this latter method should not be discarded until its possibilities have been fully explored.

INTRODUCTION

This study was conducted as part of an investigation to develop a moisture meter suitable for measurement of transient moisture gradients in concrete pavements. It is concerned with the relationships between the dielectric properties -- dielectric constant and dielectric conductivity -- of hardened concrete to the water content of the concrete. The possible utilization of these properties for in situ measurements by non-destructive methods of the transient moisture gradients in concrete pavement slabs was investigated.

A preliminary literature survey of existing moisture-measuring methods was conducted (5)*. This survey suggested that a capacitance type moisture meter might be well suited to the proposed application. The apparent advantages of the capacitance method were: relatively inexpensive and simple instrumentation, an inert sensing element, comparative freedom from the influence of changing salt concentrations of the pore fluids, sensitivity and immediate response to small moisture changes. While the capacitance method has not been tried as a moisture indicator in concrete, it has been investigated for soil and for a wide variety of other substances. Therefore, a study was initiated to investigate the application of the capacitance type moisture meter to hardened concrete and, if found feasible, to develop such a meter.

Preliminary capacitance measurements (5) on Portland Cement mortar specimens indicated that a capacitance moisture meter might be

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* Numbers in parentheses refer to references in the Bibliography

feasible; however, the information available was insufficient to permit design of the necessary instrumentation and procedures to evaluate this method conclusively. The investigations reported herein were conducted to provide this information and had the following purpose and scope:

1. Establish quantitatively the relationships between the significant dielectric properties of hardened concrete and water content within such limits as required to permit the design of a capacitance moisture meter if its feasibility were indicated.

2. Study calibration, measurement, and interpretation procedures which could be applied to in situ transient moisture gradient investigations.

3. Determine the inherent feasibility of utilizing the capacitance moisture meter in this application.

The report is divided into two parts. The first part consists of a survey of the capacitance method as it has been utilized by others, a summary of the theory of high loss dielectrics such as concrete, and a review of the pertinent methods of capacitance measurement, which provided the basis for the experimental approach used. The second part consists of a laboratory study of the dielectric constant-water content and the dielectric conductivity-water content relationships for one mortar and one concrete mix through ten cycles of drying and wetting.

In these tests, one half of the samples was over dried to 105°C and the other half was dried to 60°C. All dielectric constant determinations were from permittivity tests made at a frequency of 10^6 cps. Dielectric conductivity was determined both from direct resistance measurements at 10 cps and from the 10^6 cps permittivity tests. Special tests were conducted to indicate the influence of the salt concentration of the pore fluid on these relationships. All procedures and equipment used in these tests were selected to be suitable for adaptation to field studies if the laboratory tests indicated that field applications were justified.

LITERATURE REVIEW AND GENERAL DISCUSSION

Literature Review

Capacitance Moisture Meters

In principle the capacitance moisture meter is a very simple device. It is based on the fact that if electrodes having a geometric capacitance C_o are embedded in a material with a relative dielectric constant κ' their capacitance will be

$$C = C_o\kappa' \qquad [1]$$

The capacitance moisture meter consists of a sensing element which is a suitably calibrated capacitor employing the material whose water content is desired as the dielectric and a device for measuring the capacitance of this capacitor. Equation 1 permits the determination of the dielectric constant of the material from these measurements. The dielectric constant of a material such as concrete is a function of its water content, and if the dielectric constant-water content relationship of the material is known, the water content can be determined from the capacitance measurements.

Such a moisture meter apparently has several advantages. The instrumentation principle is simple; the sensing element is inert and does not depend on a moisture equilibrium between some hydrophilic material and the material being measured. The moisture is sensed by an

electric field and therefore gives immediate response to transient moisture changes. Also, the relative dielectric constants of most solid minerals are in the range from 5 to 10 (6) while the value for water may be on the order of 80 (12), indicating that the method should have high sensitivity to small moisture changes.

Two important assumptions are implied in the capacitance method of measuring moisture contents. First, it is assumed that the capacitance of the sensing capacitor can conveniently be measured in such a way as to reflect truly the dielectric constant of the material being studied, and second, it is assumed that the dielectric constant-water content relationship is constant for the conditions of the investigations and can readily be determined by some appropriate calibration procedure. To evaluate the true potential of this method in a given set of circumstances, the validity of these assumptions must be established for the conditions of the particular situation.

Reference could not be found in the literature to the study of the capacitance method relative to concrete, but the apparent advantages of this method have led numerous investigators to study its application to moisture determination in a wide variety of other materials including soils, soybeans, wheat, cotton, gelatin, paper pulp, carrots, and beef steak.

One of the most striking characteristics of these researches is the lack of consistency in the results. For example, Balls (3) reports excellent results with cotton and found an almost linear relationship between water content and measured capacitance, while Lill (24), working with soils, was unsuccessful primarily due to an inability to balance

out or otherwise compensate for stray capacitances and the effects of the conductivity of the soil. Lill used a tuned oscillator circuit instead of a capacitance bridge which most other investigators have used to measure the capacitance. He attributes most of his instrumentation problems to this fact and suggests that a "Schering" type bridge would have been superior. Lill also used insulated electrodes and noted that the cell was very sensitive to the degree of contact between the cell and the soil. He further states that the cell was more sensitive to changes of the conductivity of the soil than to capacitance changes. Most of the other investigators claim limited success, depending upon their purposes. The best results were generally obtained with the simpler materials such as gelatin and cotton, and the least success was achieved with the more complex materials, notably soils. The following discussion is restricted to studies on soils and rocks, unless otherwise noted, as these materials have more in common with concrete than do many of the others.

Balls (3), using a tuned oscillator and insulated electrodes, obtained relatively consistent results at a frequency of 2×10^6 cps with soils. His data showed that the capacitance increased by a factor of 5 as the water content was increased from 0 to 60 per cent.

DePlater (11), utilizing a bridge circuit at 1000 cps and bare electrodes, reports consistent results on a "clay loam" and indicates that the capacitance of his setup depended only on the water content of the soil. Cashen (7), however, who measured the equivalent parallel capacity and conductance of a series of soil blocks, obtained results which depended on the electrodes used. With mercury electrodes, all

soils gave capacitance-water content curves of the same general type, which he attributes to a large capacitance of the soil-electrode interface. Results using carbon electrodes were less consistent but showed the same general effects.

Willihan (40), using a modification of the capacitance method incorporating a plaster of Paris block between the electrodes, obtained consistent results with insulated plates, but the use of non-insulated plates was unsuccessful where the electrical resistance between the plates was as low as 10 ohms. He also reports that the frequency of the alternating voltage used in the bridge apparently did not affect the results obtained with insulated plates. With non-insulated plates, however, low frequencies gave the highest readings. Banerjee and Joshi (4) who studied the dielectric constant of soil at radio frequencies also found that the dielectric constant decreases with an increase of frequency and that the relative dielectric constant increased from about 4 or 5 at a water content of 14% when measured at a frequency of 70×10^6 cps.

Cownie and Palmer (9), investigating the effect of moisture on the electrical properties of soil at a frequency of 430×10^6 cps using a coaxial transmission line terminated with clay samples as their test cell, found that the relative dielectric constant varied from 4 to 31 as the water content was increased from 4 to 47%. These results compared favorably with data at very high frequencies from other investigators they cited. They also found that the dielectric constant increased first at an increasing rate with water content and then at a decreasing rate at the higher water contents. This double inflection could not be

predicted by simple mixing theories. They explain this phenomenon on the basis that the first water added to the soil (below about 15 to 20%) is strongly held by the force fields of the clay and, acting as bound water, has a dielectric constant of the same order as ice, while water above 20% acts as free water with a relative dielectric constant of about 80. Edlefsen (13), in discussing the dielectric method and summarizing the findings of several investigators, points out that a given quantity of water distributed evenly through a soil produces a greater change in the dielectric constant of comparatively dry soil than it does in the same soil when relatively wet, and contrary to the results of Cownie and Palmer, states that the relation is practically linear up to the moisture equivalent of the particular soil. Edlefsen also points out that the dielectric constant decreases, other factors being constant, as the temperature increases. This is supported by the fact that the dielectric constant of water decreases with increasing temperature (12). He also states that the dielectric constant of the soil water system is a function of the salt concentration of the pore water. Fletcher (16) also reports an influence of the salt concentration of the pore fluid at 3.9×10^6 cps but only for concentrations of less than 0.1 gm per 100 cc in the case of NaCl, which was the only salt he investigated. Addition of NaCl in excess of this amount had no additional effect. This point is confused rather than clarified when free water is considered because Hasted (20), Smith-Rose (32), and Von Hipple (39) all indicate that the salt concentration of bulk water has only a small effect on its dielectric constant at frequencies in the low megacycle range. However, Hasted (20) also presents data showing that salt

concentrations greater than about 1 Normal significantly decrease the dielectric constant of water for frequencies greater than $1,000 \times 10^6$ cps.

Anderson (2) measured the capacitance of several soils as a function of water content using bare electrodes at a frequency of about 1,000 cps. He found that the curves for all soils were very similar with the capacitance increasing very rapidly with water content up to approximately the moisture equivalent of the soil and remaining nearly constant for higher water contents. Anderson also found that the increase in capacitance with water content was about 450 μμf as opposed to a predicted value of about 16 μμf assuming a relative dielectric constant of 5 for the solids and 80 for the water. He suggested that the anomalously high dielectric constants could be the result of very high polarizability of the adsorbed water layer or as a result of polarization of the non-insulated electrodes. He also stated that contact between the electrodes and the soil is not important as long as it is reproducible, which was the case for the soils he tested. On the other hand, Childs (8), in a discussion of electrical methods of measuring soil moisture, shows that for certain conditions of low frequency and high conductivity of the dielectric it would be possible for contact capacitances to produce high capacitance readings such as those reported by Anderson.

Anomalous dielectric constant values have also been measured for a wide range of materials other than soils. Most significant to this study are those for rocks. Evjen (14) estimated a value for the relative dielectric constant of a sedimentary rock section to be 10^8. Recently Keller and Licastro (23) have measured values greater than 10^6 for sedimentary cores in the natural state. Keller and Licastro made

their measurements at frequencies ranging from 50 cps to 30×10^6 cps. They found the very high values at the lower frequencies. At frequencies above 10×10^6 cps all values were less than 80. This dispersion effect was only significant for wet cores and is obviously associated with the contained water. These investigators also measured the resistivity of these cores. The wetter cores show an almost constant resistivity for the lower frequencies decreasing with frequency only above about 10^6 cps. The dry cores on the other hand show an almost linear decrease with frequency on a log-log plot for the full range of frequencies studied. A portion of their data is reproduced in Figure 1.

Keller and Licastro show, based on a dispersion model proposed by Jolliffe (22), that the dielectric constant values measured are much too high to be attributed entirely to electrode polarization. They further explain the anomalously high dielectric constants on the basis of an interfacial or space-charge polarization phenomena.

Dielectric Properties of Concrete

Very little actual data is available pertaining to the dielectric properties of concrete. A paper by Hammond and Robson (17) contains the only data on the dielectric constant which could be found in the literature. Steniour (35) has referred to the results in this paper as the standard for the cement industry. These workers found anomalously high dielectric constants and dispersion for frequencies in the range of 50 to 25,000 cps. They also obtained somewhat different values for different types of cement, and the dielectric constant values for pastes were significantly higher than the corresponding values for concrete. All that can be learned about the dielectric constant-water content

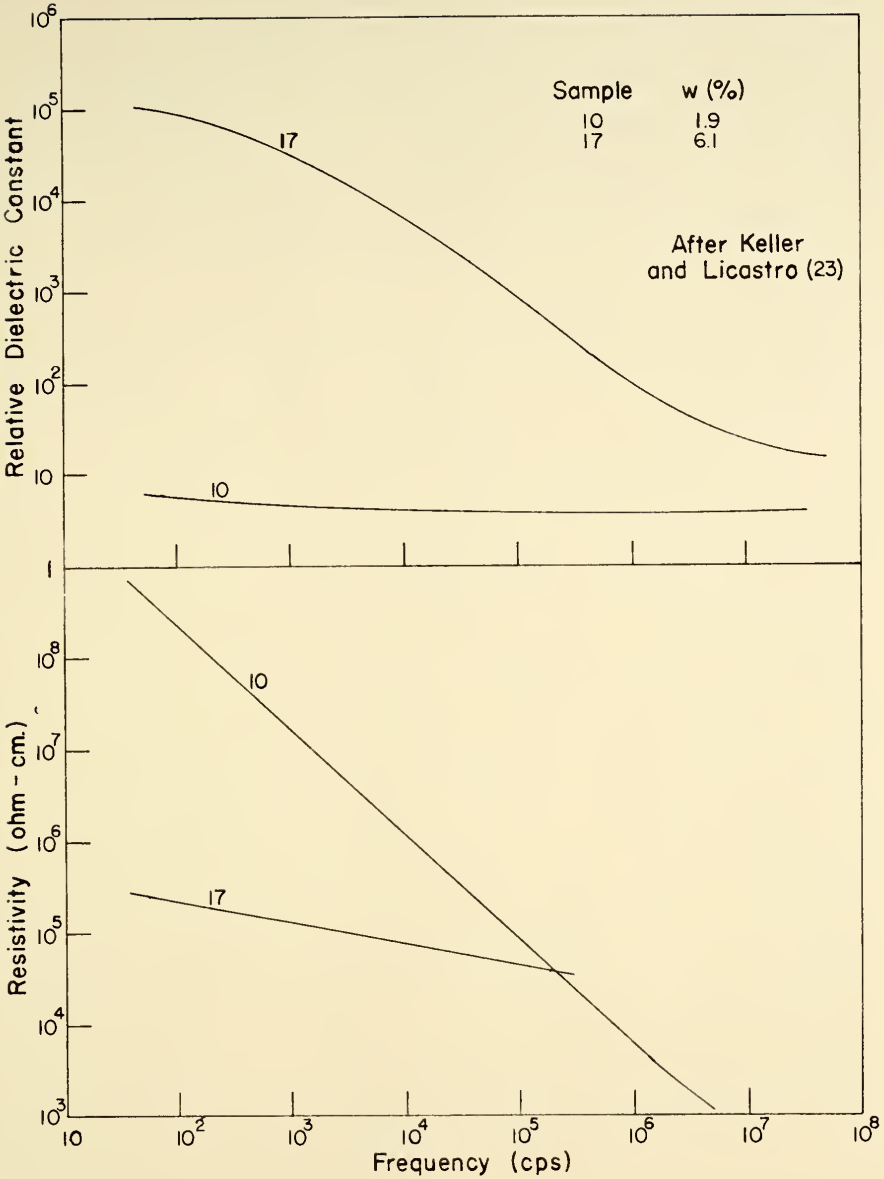

FIG. 1 RELATIVE DIELECTRIC CONSTANT AND RESISTIVITY OF NATURAL-STATE MORRISON CORES

relationship from these data is that within the range of the relatively low water contents tested the dielectric constant generally increases with increases in water content. A portion of Hammond and Robson's results are presented as Figure 2. The trends of these results are in general consistent with those of Keller and Licastro (23) for rocks (Figure 1).

The conductivity of concretes and pastes have been studied by several investigators, and it is generally accepted that this property is strongly influenced by several factors other than water content. Spencer (34) studied this property in 1938 and states that at the same water content resistivity of a concrete may vary by 40% with changes in salt content of the pore fluid. Decoux, Roland, and Barnes (10) find that the resistivity at a given water content of a fresh concrete may vary from that of an aged concrete by a factor of 100 because of salts in the pore fluid. They also show that certain admixtures such as blast furnace slag can have a significant effect on the conductivity.

The conductivity of concrete must also be strongly affected by the mix design, curing, and other factors. Powers, Copeland, and Mann (29) present results which show that water-cement ratio, type of cement, curing, and fineness of cement can control whether or not the hardened cement paste will contain continuous capillary pores. Whether or not the cement paste of a concrete contained continuous capillaries would certainly have a pronounced effect on the electrical conductivity of the concrete.

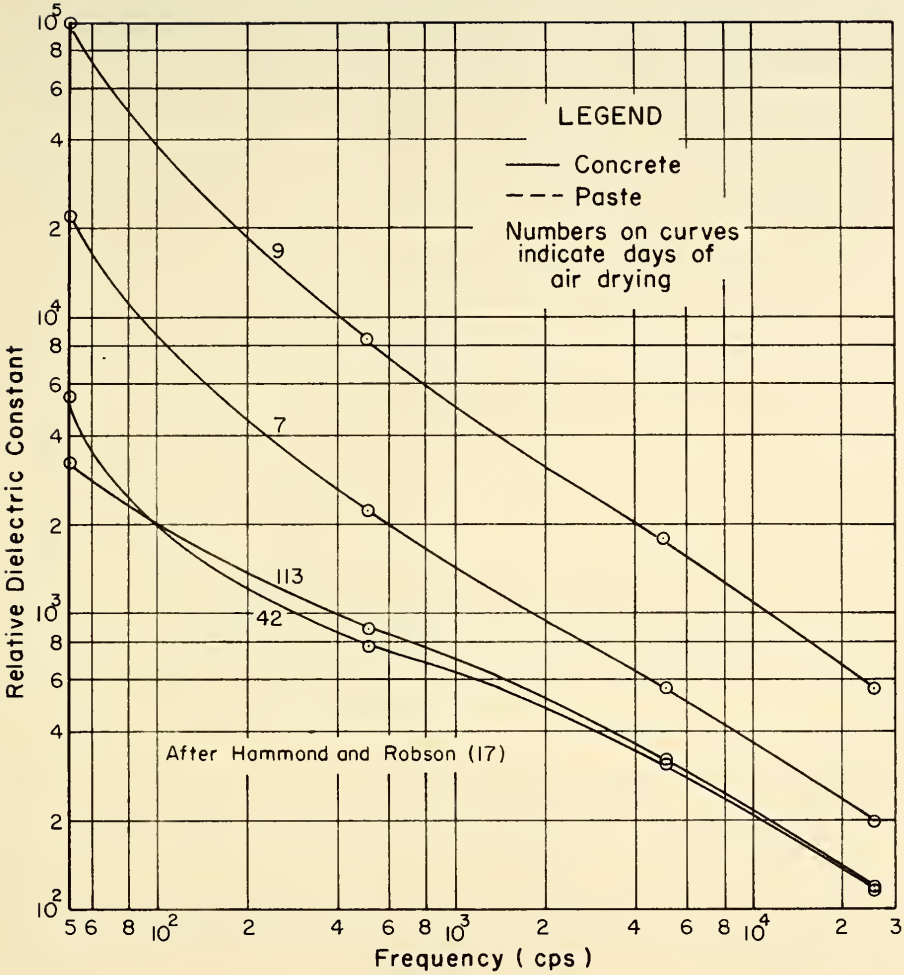

FIG. 2 RELATIVE DIELECTRIC CONSTANT OF CONCRETE

Theory of High Loss Dielectrics

The general theory of dielectrics is a broad topic, and the volume of literature relative to it is immense. Several massive reviews and bibliographies have been compiled, and a few of these are listed under General References in the List of References. This section reviews only those aspects of the general theory which are most necessary to explain some of the apparently contradictory results recorded in the moisture meter literature and to understand the general dielectric behavior of a high loss porous dielectric such as moist concrete. The literature concerning such dielectrics is much less abundant than for more ideal materials.

Von Hippel (38) states,

> The structure and behavior of isolated atoms and molecules and the behavior of electrons and ions in gases of low pressure are now relatively well understood; the dielectric properties of gases at high pressure and of liquids and solids are still known only in rough outlines.

Therefore, concrete does not lend itself to the elegant theories applicable to ideal materials, and only the most general of treatments is possible.

If a sinusoidal voltage

$$V = V_o e^{j\omega t} \qquad [2]$$

is applied to a capacitor with a geometric capacitance C_o incorporating a leaky dielectric with dielectric constant ϵ' and a conductance G, the capacitor will store a charge

$$Q = \frac{\epsilon'}{\epsilon_o} C_o V \qquad [3]$$

where ϵ_o is the dielectric constant of free space (vacuum). The relative dielectric constant

$$\kappa' = \frac{\epsilon'}{\epsilon_o} \qquad [4]$$

and from Equations 1 and 3

$$Q = CV \ . \qquad [5]$$

This capacitor will have a charging current

$$I_c = j\omega CV \qquad [6]$$

leading the voltage by a phase angle of 90° and a loss current

$$I_\ell = GV \qquad [7]$$

in phase with voltage. The total current drawn by the capacitor will be

$$I_c + I_\ell = (j\omega C + G)V \qquad [8]$$

having a power-factor angle θ from the applied voltage and a loss angle δ from the j axis. The loss of a dielectric is often designated in terms of dissipation factor D or loss tangent tan δ:

$$D \equiv \tan \delta \equiv \frac{I_\ell}{I_c} \ . \qquad [9]$$

It is convenient to express these relationships in terms of the complex permittivity ϵ^*

$$\epsilon^* = \epsilon' - j\epsilon'' \qquad [10]$$

such that the total current is

$$I = (j\omega\epsilon' + \omega\epsilon'')V \frac{C_o}{\epsilon_o} = j\omega V C_o \kappa^* \qquad [11]$$

where κ^* is the complex relative permittivity

$$\kappa^* = \frac{\epsilon^*}{\epsilon_o} = \kappa' - j\kappa'' \qquad [12]$$

and ϵ'' and κ'' are the loss factor and relative loss factor respectively. The loss tangent may now be written

$$\tan \delta = \frac{\epsilon''}{\epsilon'} = \frac{\kappa''}{\kappa'} \qquad [13]$$

For this notation, the current density J traversing a parallel plate capacitor under an applied field strength E is

$$J = (j\omega\epsilon' + \omega\epsilon'')E \qquad [14]$$

Representing current density graphically (Figure 3), it is apparent that the quantity

$$\sigma = \omega \epsilon'' \qquad [15]$$

has the properties of conductivity and therefore is called dielectric conductivity.

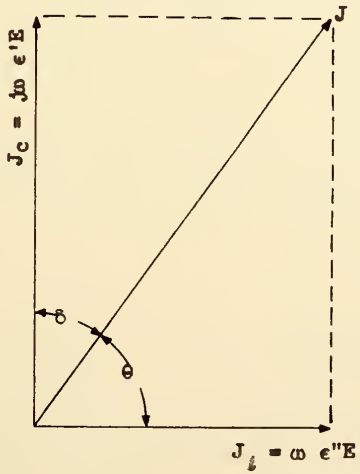

Fig. 3. Current Densities of a Capacitor with Loss.

To completely describe the electrical properties of a dielectric, it is necessary to define the complex permeability μ^* as well as the complex permittivity ϵ^*. However, for the purposes of this discussion, it is reasonable to assume the magnetic effects of concrete as negligible and consider only the complex permittivity.

A dielectric material inserted between the plates of a capacitor increases the storage capacity of the capacitor by neutralizing charges at the electrode surfaces. If a dielectric composed of dipolar molecules is assumed, this neutralization may be visualized as the result of dipole orientation as represented schematically in Figure 4.

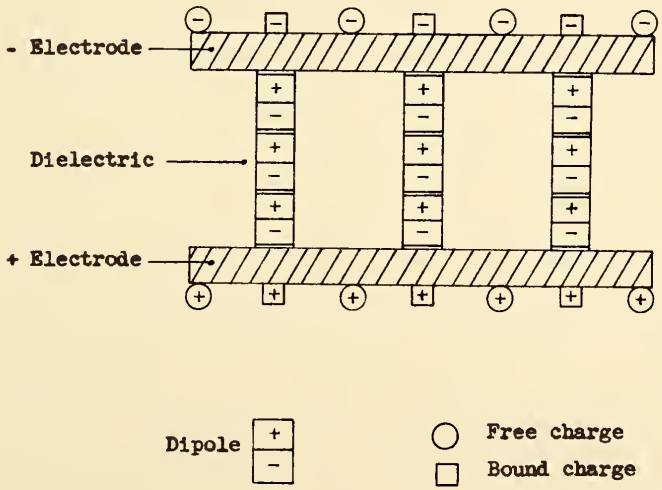

Fig. 4. Schematic Representation of Dielectric Polarization.

The process of orientation of charges to oppose the applied field is known as dielectric polarization and was first recognized by Faraday prior to 1837. Polarization P is defined as the bound charges per unit area at the surface of the electrodes, and it is proportional to the ease with which a dielectric may be polarized or its polarizability α. The polarizability may be defined as the average polarization per unit field strength per contributing elementary particle.

The polarization is related to the dielectric constant of a dielectric material through

$$P = (\kappa' - 1)\, \epsilon_o E \quad . \qquad [16]$$

This expression shows that the dielectric constant cannot be a constant because through its relationship with polarization it is also a function of the polarizability which is influenced by such variable factors as temperature, frequency of the applied field, and the presence of local fields. In general, increasing temperature will decrease the value of the dielectric constant by raising the activation level of the molecules and increasing the difficulty of orienting them in the applied field. Likewise increasing frequency will decrease the dielectric constant by making it more difficult for the dipoles to change their orientation rapidly enough to follow the field alterations. Local electrical fields may also reduce the dielectric constant by tending to hold the dipoles in fixed positions making it more difficult for them to rotate to oppose the applied field.

It is also possible to draw some conclusions concerning the significance of the dielectric conductivity σ. The dielectric conductivity will not only include the actual ohmic conductivity associated

with the migration of free charge carriers through the dielectric but will also reflect the power losses in overcoming the opposition to orientation of the dipoles. Both of these factors are functions of temperature, and the latter is a function of frequency and other fields; therefore, it must be expected that the loss factor ϵ'' is also a variable dependent on temperature, frequency, and other fields.

The relationship between charging and loss current densities (Figure 3) suggests the representation of capacitors with loss by circuits composed of lumped ideal capacitances and resistances. The most obvious such representation is the simple parallel RC circuit. When this circuit is connected to an AC voltage source, the current becomes

$$I = (j\omega C + \frac{1}{R})V \ . \qquad [17]$$

For electrical equivalency of this RC circuit to a real capacitor with a leaky dielectric, its current must be identical in magnitude and phase with that of the real capacitor. From Equations 11 and 17

$$(j\omega C + \frac{1}{R})V = (j\omega\epsilon' + \omega\epsilon'')V \ \frac{C_o}{\epsilon_o} \qquad [18]$$

and it follows that

$$\kappa' = \frac{C}{C_o} \qquad [19]$$

$$\sigma = \frac{\epsilon_o}{R\,C_o} \qquad [20]$$

and

$$D = \tan\delta = \frac{1}{\omega RC} \qquad [21]$$

where C and R are the equivalent parallel ideal capacitance and resistance respectively, C_o is the geometric capacitance of the real capacitance,

κ' and σ are the relative dielectric constant and dielectric conductivity of the real dielectric at the angular frequency ω, and δ is the loss angle for this dielectric. It must be remembered that R is not the ohmic resistance of the dielectric but is a purely conductive resistance which dissipates the same power as that lost in the dielectric by conductance plus all other power-consuming phenomena. Any two of these equations completely describe the real dielectric in terms of an equivalent parallel circuit composed of R and C.

The analogy between a real capacitor and a RC circuit of ideal lumped circuit components is a very useful concept in many applications. It provides the basis for bridge measurements of capacitance, which will be discussed later. There is an infinite number of equivalent circuits which could be used; however, the simple two component parallel RC circuit is doubly convenient because of its simplicity and because the relationship between the conductance of a real capacitor and the equivalent parallel resistance is easy to visualize. This circuit is adequate for many applications with high loss dielectrics. It will not, however, adequately represent the response of a real dielectric with loss to all frequencies unless the R and C values are varied accordingly. This is illustrated by Figure 5. If an equivalent RC circuit with single valued components which will represent the frequency response of a real capacitor with loss is desired, a more complex equivalent RC circuit (such as the one shown on Figure 5) must be used. The specific equivalent circuit which will be most applicable will depend on the frequency characteristics of the dielectric in question.

Defining a dielectric in terms of its complex permittivity

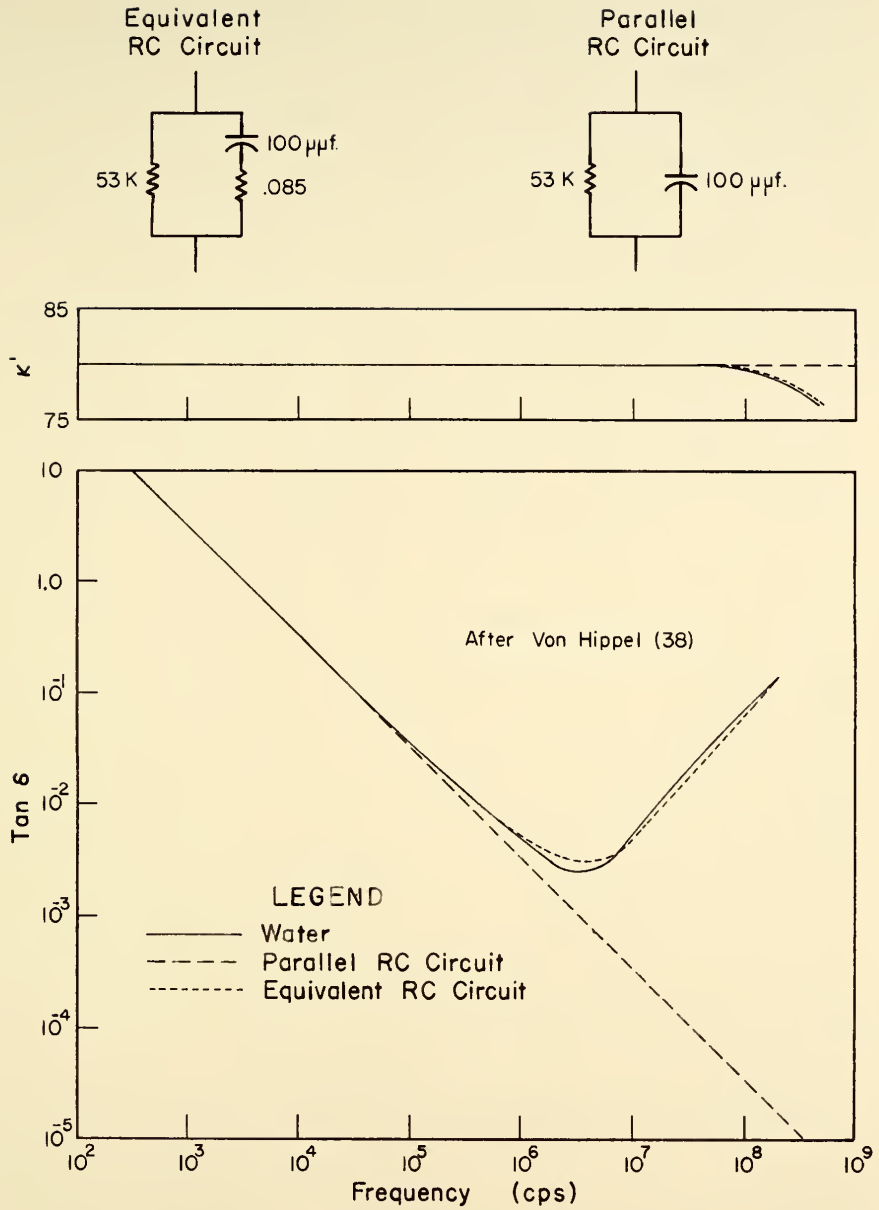

FIG. 5 FREQUENCY RESPONSE OF WATER AND ITS REPRESENTATION BY RC CIRCUITS

provides a basis for dielectric constant measurements. It permits the determination of the polarizability and of the frequency spectrum of a dielectric; however, to understand why a dielectric behaves as it does, or to predict dielectric behavior, the response of the material to an electric field must be examined on a microscopic scale.

A dielectric material contained in a capacitor increases the storage capacity of the capacitor by neutralizing charges at the electrode surfaces. The effectiveness with which a given dielectric material performs this function is controlled by the dielectric's ability to polarize in opposition to the impressed electric field. Four mechanisms of polarization are recognized: 1) electronic, 2) atomic, 3) orientation, and 4) space charge or interfacial polarization.

The first three polarization mechanisms are all forms of the dipole polarization previously discussed and are due to charges locally bound in atoms, in molecules, or in the structures of solids and liquids. They result from permanent molecular dipoles (orientation polarization) or dipoles induced by external fields in atoms (electronic polarization) and in molecules (atomic polarization). The fourth type--space charge (or interfacial) polarization--results from charge carriers that are usually present and more or less free to move through the dielectric under the influence of the applied field. When such carriers are impeded in their movement and become trapped in the material or at interfaces, space charge concentrations result in a macroscopic field distortion which increases the capacitance.

The total polarizability α is the sum of the electronic polarizability α_e, the atomic polarizability α_a, the orientation polarizability α_o,

and the space-charge polarizability α_s.

$$\alpha = \alpha_e + \alpha_a + \alpha_o + \alpha_s \ . \qquad [22]$$

The relationship between the microscopic and macroscopic approaches is given by the definition of polarizability which leads to

$$P = N \alpha E' \qquad [23]$$

where N is the number of contributing elementary particles per unit volume of average polarizability α acted upon by the local electric-field E' and by Equation 16 which relates polarization to dielectric constant. For gases at low pressures, E' may equal the externally applied field E, but for gases at high pressure and for liquids and solids, this is not the case because of the interaction of molecules. There are theories relating microscopic structure to the dielectric constant for gases at low pressures and some pure liquids and crystals, but at the present time this is completely out of the question for complex systems such as concrete. Microscopic considerations, however, do aid in qualitatively understanding some of the observed phenomena.

As previously stated, the dielectric constant is not a constant. It is apparent that not only is the dielectric constant a function of frequency, temperature, and local fields, but is also a function of applied field strength, the availability and freedom of charge carriers within the dielectric, and local field distortions. The variation of dielectric constant with frequency is called the dispersion of the dielectric constant. This dispersion phenomenon is illustrated by the frequency response of rock (shown in Figure 1). Dispersion results from the fact that the various polarization mechanisms are not equally

effective at all frequencies. The relative frequency response of these mechanisms is illustrated on Figure 6.

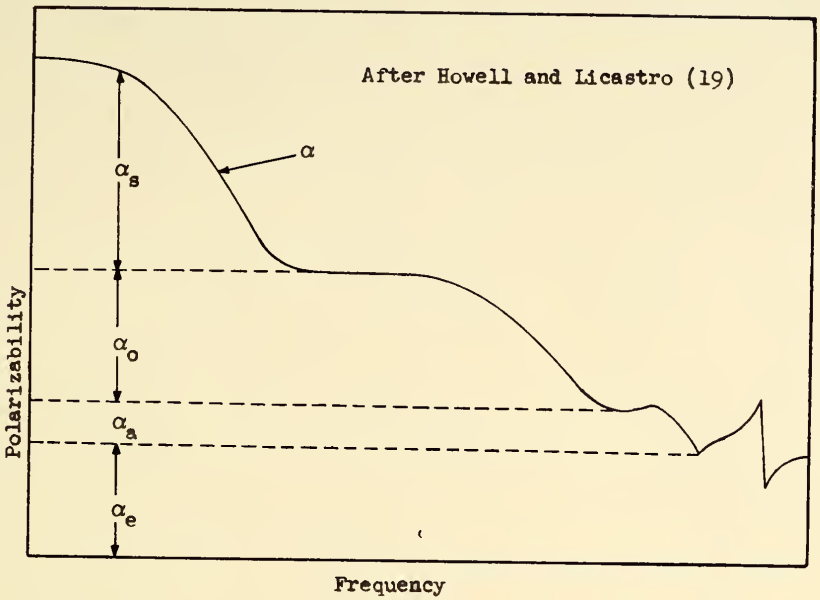

Fig. 6. Idealized Graph of Relationships Between the Polarization Mechanisms and Frequency

The dielectric conductivity will also show the influences of the above factor. This is true because dielectric conductivity is a function not only of ohmic conductivity but also of the power consumed in polarizing the material; therefore, it must reflect the control these factors have over the polarizability of the material. This phenomenon is illustrated by the data for water in Figure 5.

Considering the work of Keller and Licastro (23) and the nature

of concrete, space-charge polarization may play an important role in concrete. This mechanism unlike the other polarization mechanisms which are produced by displacement of bound charges is produced by traveling charges. Space-charge or interfacial polarization was recognized first prior to 1892 by Maxwell (26), whose classical two-layer capacitor serves as a model for this polarization mechanism. In this model the dielectric consists of two sheets characterized by their dielectric properties κ_1', σ_2 and κ_2', σ_2 respectively, and $\sigma_1 > \sigma_2$. This compound dielectric possesses a dielectric constant dispersion which is macroscopically indistinguishable from the dispersion spectrum for simple orientation polarization; however, the loss factor contains in addition to an orientation loss term an ohmic-conductivity term caused by the σ_1 and σ_2 factors which distort its dispersion curve. From the molecular point of view, because of the unequal conductivities, charge carriers pile up at the interface between sheet 1 and sheet 2 and cause field distortions resulting in a higher dielectric constant than would be predicted from a simple series combination of the capacitances resulting from κ_1' and κ_2'.

Von Hipple (38) has shown that dividing the layers 1 and 2 into thinner layers and arranging them in any manner does not affect the complex permittivity of the resulting dielectric. However, a change of the relative geometry of the two media, for example from the sheets to cylinders or spheres of material 1 in a matrix of material 2, results in a very different permittivity (31). It is apparent that the simple mixing rules frequently used, such as the logarithmic rule, where the dielectric constant of a mixture κ_m' of two materials of dielectric

constants κ_1' and κ_2' and volume fractions ϕ_1 and ϕ_2 is expressed by

$$\log \kappa_m' = \phi_1 \log \kappa_1' + \phi_2 \log \kappa_2' \qquad [24]$$

can hold true only for very specific special distributions which eliminate space-charge polarization. The volume fraction is the ratio of the volume of the material to the total volume of the mixture.

If space-charge polarization is to be avoided, the charge carriers must be able to move freely through the dielectric, be capable of discharging freely at one electrode, and be replaced simultaneously at the other electrode. This combination of conditions is very unlikely in non-metals (37). Space-charge polarization at the interface between the dielectric and the electrodes has received much notoriety under the name of electrode polarization; however, until very recently it has been almost completely overlooked as a possibility within the body of the dielectric. It is, of course, impossible to predict quantitatively the dielectric constant-water content relationship of a concrete, but these considerations assist materially with the interpretation of permittivity measurements.

Permittivity Measurements

A variety of methods has been developed to determine the dielectric properties of materials. The primary factors controlling the method best suited to a given application are the frequency at which the measurements are to be made and the loss of the dielectric. For frequencies up to about 10^8 cps, lumped circuits are used, and above 10^8 cps, distributed circuits are used to determine permittivity. Neither complex permittivity nor its components, dielectric constant and loss factor, are measured directly but are calculated from measurements of

other parameters. Which parameters are measured depends on frequency range used.

Very low frequencies are not suitable for moist concrete because of the high concentration of mobile ions which lead to electrode problems. Very high frequencies result in increased instrumentation problems. In the frequency range from about 10 to 10^7 cps the most generally useful method for dielectrics with loss is the AC bridge method (33). In this method the parameters measured are usually relative capacitance and dissipation factor. The dielectric constant and loss factor or dielectric conductivity are obtained by suitable calculations using these parameters.

Figure 7 is a block diagram of the AC impedance bridge. By proper design and selection of the components making up the various

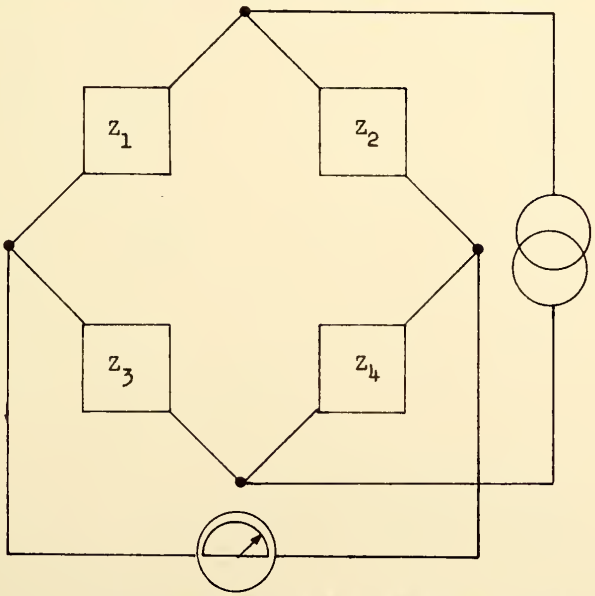

Fig. 7. Block Diagram of the AC Impedance Bridge

impedances, this bridge may be used to measure resistance, capacitance, or inductance. In any case, for balance (zero current through the detecter) both of the following conditions must be satisfied.

$$\frac{Z_1}{Z_2} = \frac{Z_3}{Z_4} \qquad [25]$$

$$\theta_1 + \theta_4 = \theta_2 + \theta_3 \qquad [26]$$

A simple capacitance comparison bridge is represented schematically in Figure 8. C_{xs} and R_{xs} are the series equivalent capacitance and resistance representing the unknown capacitance to be measured. The

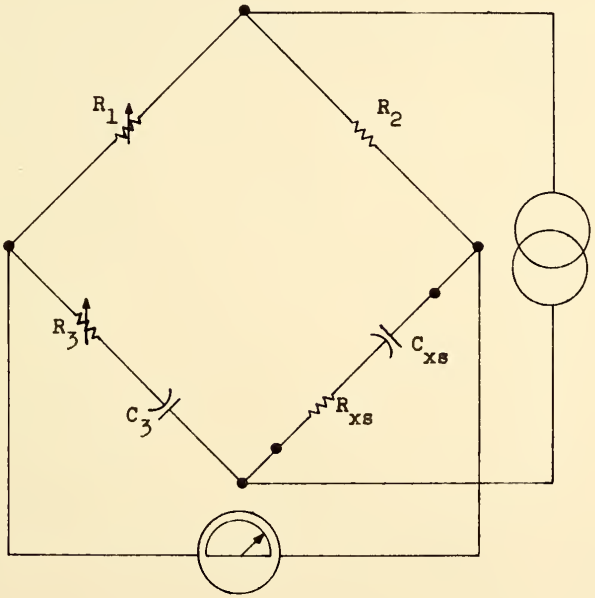

Fig. 8. Simple Capacitance Comparison Bridge.

balance equations for this bridge are

$$\frac{R_2 R_3}{R_1} = R_{xs} \qquad [27]$$

and

$$C_3 \frac{R_1}{R_2} = C_{xs} \qquad (28)$$

For the two unknowns there must be two variable bridge components to permit balancing the bridge. In this case they are R_1 and R_3. R_1 may be given a dial calibrated in resistance units to give the value of R_{xs}, and R_3 may have a dial calibrated in capacitance units to yield the value of C_{xs} when R_1 and R_3 are adjusted for balance.

Figure 9 is a schematic diagram of the basic Schering bridge circuit.

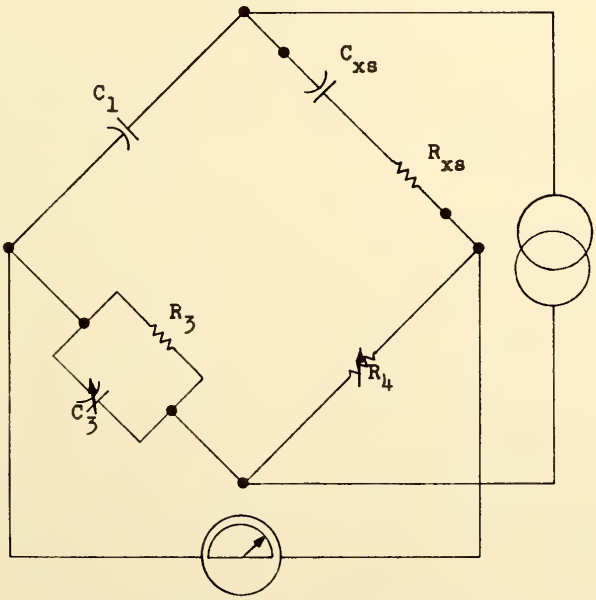

Fig. 9. Basic Schering Bridge Circuit

The balance equations for this bridge are

$$\frac{C_3}{C_1} R_4 = R_{xs} \qquad [29]$$

and

$$C_1 \frac{R_3}{R_4} = C_{xs} \qquad [30]$$

In this circuit C_3 and R_4 are the variable components and to achieve balance with the unknown capacitor represented by the series equivalent components C_{xs} and R_{xs}. A dial on R_4 calibrated in capacitance units may be used to indicate the value of C_{xs}. For this bridge the dissipation factor can be expressed

$$D_x = \frac{1}{\omega C_3 R_3} \qquad [31]$$

therefore, a dial on C_3 is usually calibrated to read the dissipation factor directly. With C_{xs} and D_x known it is a simple matter to calculate dielectric constant and loss factor.

As the frequency is increased, stray capacitances and inductances within the bridge become important, and appropriate compensating components, as well as shielding, must be added to the bridge, greatly complicating its design, construction and calibration.

The values for C_{xs} and D_x indicated by the bridge are not equal to the respective values for the sample being measured. C_{xs} and D_x contain other capacitance and loss terms. The leads connecting the sample and bridge have capacitance and resistance which increase both C_{xs} and D_x. Also there will be fringe capacitances between the electrodes around the sample and stray capacitances between the high electrode

and ground. These extraneous effects must be eliminated either by appropriate equipment design or by calculations. Detailed procedures for handling these factors are given by Field (15).

Another extremely important consideration in capacitance measurements is the quality of the contact between the electrodes and the sample being tested. If this contact is less than perfect, there will be a contact capacitance C_c in series with the specimen capacitance C_s. Considering perfect capacitors without loss, the total capacitance C_x would be

$$C_x = \frac{C_c C_s}{C_c + C_s} \qquad [32]$$

From this expression, $C_x \to C_s$ as $C_c \to \infty$ and $C_x = \frac{C_s}{2}$ for $C_c = C_s$. Therefore, unless the contact capacitance is much greater than the specimen capacitance, C_c must be determined and its influence taken into account.

General Discussion

In the review of capacitance moisture meter literature, the most striking feature was the lack of consistency between the results and conclusions of the various investigations. In the first place, some of the work was done over thirty years ago with much cruder equipment than that currently available. Secondly, extensive reviews of dielectric properties and their measurement, such as that by Von Hippel (38), were not available to earlier investigators. In addition, prior knowledge of the dielectric properties of the material being investigated was lacking. Therefore, instrumentation had to be designed more or less empirically, leaving much to chance. Attempts to evaluate this literature

are complicated by the fact that the results are often presented in terms of capacitance and resistance, which are dependent on instrumentation details, that are incompletely described. While some of the studies reported are of excellent quality, it is difficult to draw definite conclusions from these sources regarding the applicability of the capacitance moisture meter concept to hardened concrete. A few points keep recurring, mostly with respect to problems encountered in the investigations, which permit certain generalizations to be made.

It is well established that the dielectric constant-water content relationship of a complex material such as soil or concrete is not constant; it is certainly a function of frequency, and there are strong indications that it is also a function of the local electrical fields acting on the pure water and its associated ionic concentration. The degree of contact between the electrodes of the sensing capacitor and the dielectric material is a very important factor. For some conditions the effect of incomplete contact can completely override the effect of changes in moisture content. Furthermore, conventional formulae for predicting the dielectric constant of a mixture of dielectrics do not apply to complex, high-loss dielectrics such as concrete. Studies have shown that it is possible for the dielectric constant of these materials, for a given set of conditions, to be greater than the dielectric constant of any of their constituents.

It is almost universally accepted in the moisture meter literature that conductivity (resistance method) is not suitable as a moisture indicator because of its sensitivity to factors other than water content, notably changes in the salt concentration of the pore water.

The limited data available on the dielectric properties of concrete

generally support the generalizations previously stated. The data show that the dielectric constant-water content relationship is a function of frequency and that anomalously high dielectric constants have been reported for concrete. The data also show that the conductivity is strongly influenced by the salt content of the pore fluid and aging of the concrete.

While the theory of high loss dielectrics does not provide a basis for quantitative predictions of the dielectric constant of these materials, it can explain the reasons for observed behavior characteristics and guide the investigator in the development of measurement techniques most suitable to a given problem. Consideration of the dipole type of polarization mechanisms shows that dielectric constant is indeed influenced by frequency, local fields, and temperature. Interfacial polarization provides an explanation of the anomalously high dielectric constants which have been observed. Since this last type of polarization depends upon the presence of free charge carriers, it also suggests that the dielectric constant-water content relationship will be a function of the salt content of the pore water and may be subject to changes brought about by structural changes in the concrete that occur with aging.

The use of dielectric properties as moisture indicators is predicated on the assumption that appropriate measurements can be made on sensing elements which will actually reflect these properties, that the relationship between these properties and water content will remain sufficiently constant during the period over which moisture determinations are desired, and that this relationship can be established by some appropriate calibration procedure. From the review of previous work

it is by no means clear whether or not these considerations can be met with sufficient precision for any given application.

The most important question is whether or not the relationships between water content and the dielectric properties of concrete remain constant to a sufficient degree of accuracy. The laboratory tests reported in this thesis were designed to provide a basis for answering this question.

Another question concerns the instrumentation problem in measuring in the field the capacitance of a sensing element that truly reflects the dielectric constant. This is a complicated instrumentation problem influenced by such factors as method of measurement, electrical frequency, conductivity of the dielectric, configuration of the sensing electrodes and whether or not they are insulated, electrode contact, electrode polarization, and stray capacitances to ground. It is apparent that instrumentation must be specifically designed for the dielectric material in question, which requires prior knowledge of the dielectric properties of the material. Therefore, a second purpose of the laboratory tests was to provide such quantitative data, and to the extent possible with laboratory tests of the type required for the first purpose, to evaluate equipment requirements and procedures suitable for field measurements. This latter consideration imposed many restrictions on the possible approaches to the laboratory investigation of the dielectric constant-water content relationship.

Field equipment must be relatively light in weight, rugged, and stable and require relatively simple power supplies and shielding. These factors, plus the high loss angle of concrete, suggest that a bridge method would be most suitable.

The loss angle of concrete exceeds the range of most bridges. Even if a special bridge were obtained which could accommodate very large loss angles, it would yield inaccurate permittivity measurements under field conditions. As the loss angle becomes very large, the total current flowing through the capacitor can be represented very closely by a purely resistive circuit with current in phase with the voltage, and the bridge balance can be effected by a resistive balance alone. Even in the laboratory, under carefully controlled conditions it is difficult to measure the capacitance component without significant error. In the field, without the possibility of shielding the sensing capacitor, it would be impossible to obtain even a reasonable approximation unless insulated electrodes are used to reduce the overall loss of the sensing capacitor. It has been shown that the electrode contact capacitance must either be very large, in which case it can be neglected, or its value must be known so that its effect can be removed by appropriate calculations. The capacitance of insulated electrodes will be finite; therefore, its value will have to be determined.

For the method to have general utility it must also lend itself to relatively simple and rapid calibration. Since it is unlikely that this relationship will follow a simple mixing law which would permit its prediction from one or two measurements, the dielectric constant will have to be determined at several water contents, which will require that the water content of the laboratory samples be varied relatively rapidly. The most suitable shape of samples would then be thin disks. These would have the additional advantage that they could be measured in a parallel plate capacitor, which permits relatively

simple calculations because of the geometry of its field, and the procedures for calibrating and correcting for the stray capacitance of these capacitors are well established (15).

A very important consideration in permittivity tests is the bridge frequency that should be used for best results. Water has a high dielectric constant because of its large dipole moment and resulting high orientation polarizability. To give the greatest sensitivity to a capacitance meter the frequency should be chosen to emphasize this polarization. Figure 5 shows that for this purpose the frequency should be below about 10^9 cps. This presents no special problem as this is higher than would be desirable from considerations of the problems associated with a portable field unit. On the other hand, very low frequencies are not suitable because the effects of electrode capacitance and space-charge polarization are greatest at low frequencies. As these effects depend on factors other than water content, it is desirable to reduce them as much as possible. Therefore, it is necessary to select the highest frequency possible without introducing serious field instrumentation problems. Considering these factors, and from the dispersion curves of Keller and Licastro (Figure 1), it appears that the low megacycle range would be best suited to the purpose of this study.

LABORATORY INVESTIGATIONS

General

Based on the considerations discussed in the preceding section, tests were designed to measure the permittivity of concrete and mortar specimens at a frequency of 10^6 cps by the AC bridge method. The samples tested were in the form of thin disks tested at various moisture contents through ten cycles of drying and wetting in an insulated parallel plate test capacitor. Tests to determine the influence of the salt concentration in the pore fluid were also conducted on several of these specimens. The dielectric constant and dielectric conductivity-water content relationships were calculated from these test results.

The dielectric conductivities of concrete and mortar mixes were also determined for similar conditions at 10 cps by direct resistance bridge measurements.

It was believed that if procedures could be developed to determine these relationships from laboratory tests then these same procedures could be used in connection with field studies and that similar procedures could be worked out using an embedded sensing capacitor of different geometry to determine the dielectric constant of a concrete pavement slab in the vicinity of the sensing element.

Instrumentation

A General Radio Type 1610-AH capacitance measuring assembly (1) is used. The assembly consists of a General Radio Type 716-CS1 capacitance bridge, 10^6 cps oscillator, null detector, power supply, and 10^6 cps filter. The Type 716-CS1 bridge is a modified Schering bridge calibrated for 10^6 cps with a direct reading capacitance range of 100 to 1150 μμf and a dissipation factor range of 0.00 to 0.56.

The capacitance test cell used in these studies is shown in Figure 10. The upper movable plate of the capacitor is attached to a micrometer head which permits direct determination of the distance between the plates. The spring in the micrometer head also makes it possible to close the capacitor on the samples with the same pressure each time. During testing the capacitor is covered with the shield shown in the photograph (Figure 10) to keep stray capacitances to ground constant. The plates of the capacitor are 3.125 inches in diameter and are insulated with Shamban Bondized Kelon-T Teflon sheet nominally .002" thick bonded to the plates with Biggs R-313 epoxy.

The total stray and fringe capacitance to ground and around the edge of the sample was estimated from direct measurement. For a given sample, the fringe and stray capacitance was taken as the difference between the total capacitance of the cell, measured with air as the dielectric for a plate spacing equal to the thickness of the sample, and the geometric capacitance of the sample.

The test capacitor was connected to the bridge with Amphenol RG-196 coaxial cable and matching connectors. This cable incorporates a Teflon dielectric.

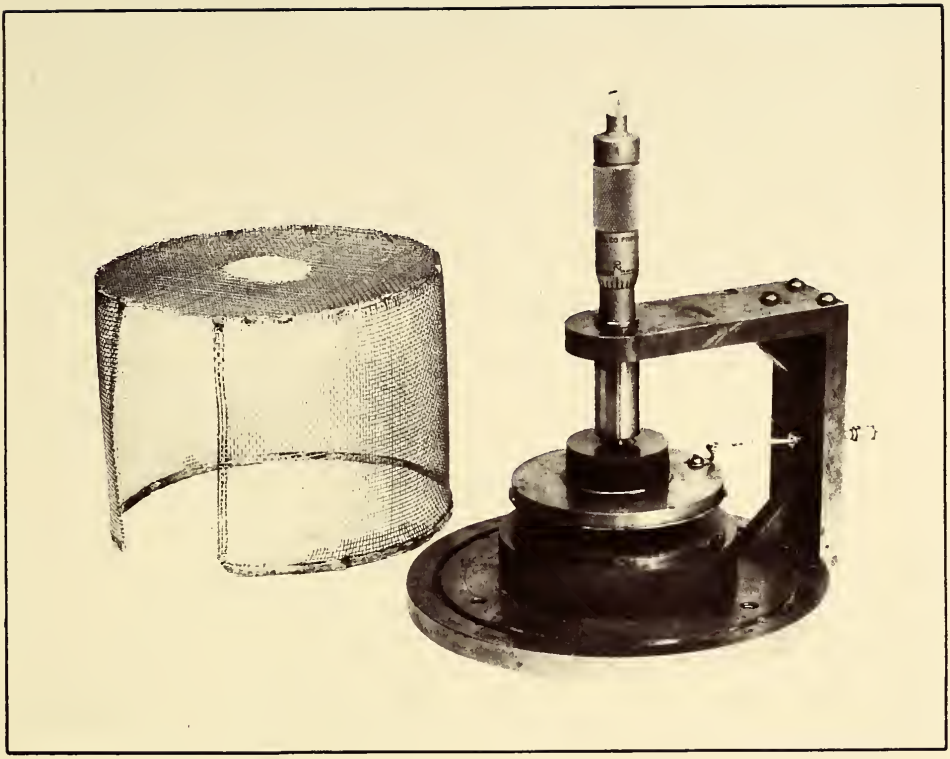

FIG. 10 CAPACITANCE TEST CELL

All tests were conducted at 30°C ± 1°C by keeping the test cell in a Cenco Model 46023 incubator.

For the resistance measurements an AC bridge was constructed. This bridge is shown schematically in Figure 11. The samples tested were prismatic in form and had such a low geometric capacitance that the capacitance component could be neglected. The ends of the samples were painted with a high conductivity silver paint, and contact between the bridge and the samples was made by holding the bridge leads to the ends of the samples with spring contacts. The bridge was driven by a Hewlett-Packard Model 202D audio oscillator, and a Tektronix Type 502 oscilloscope was used as a null detector.

Procedures

Sample Preparation

Two types of samples were prepared for these tests: disks for the permittivity tests and prisms for the resistance tests. Two mixes were used for each: a mortar mix of 1, $2\frac{1}{2}$, and 2/3 parts of cement, fine aggregate, and water by weight, and a concrete mix of a 1, 2, $1\frac{3}{4}$, and 2/3 parts of cement, fine aggregate, coarse aggregate, and water. Type I Portland cement and tap water were used in these mixes. The aggregate was a dolomitic limestone from the Rensselaer, Indiana, quarry. It was crushed and graded as shown on Figure 12.

These ingredients were batched in quantities sufficient for two 3-inch diameter by 6-inch cylinders and were blended in a mechanical mixer. Two cylinders of each mix were prepared. The fresh mix was placed in greased, split, cylindrical molds, covered with wet cloths

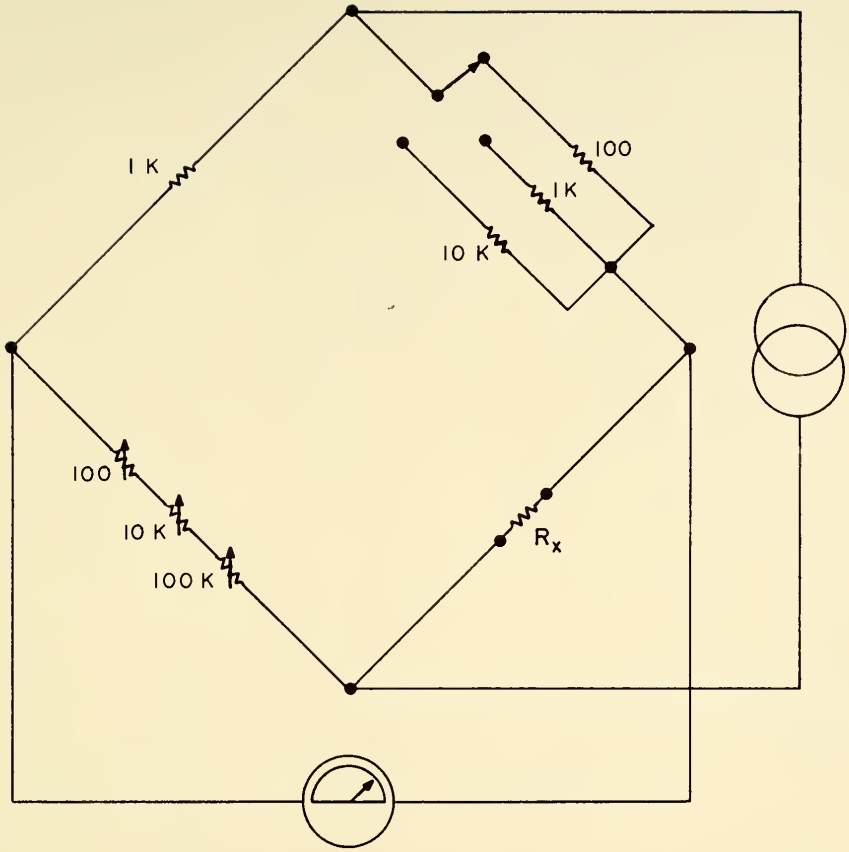

FIG. 11 SCHEMATIC DIAGRAM OF RESISTANCE BRIDGE USED FOR CONDUCTIVITY TESTS

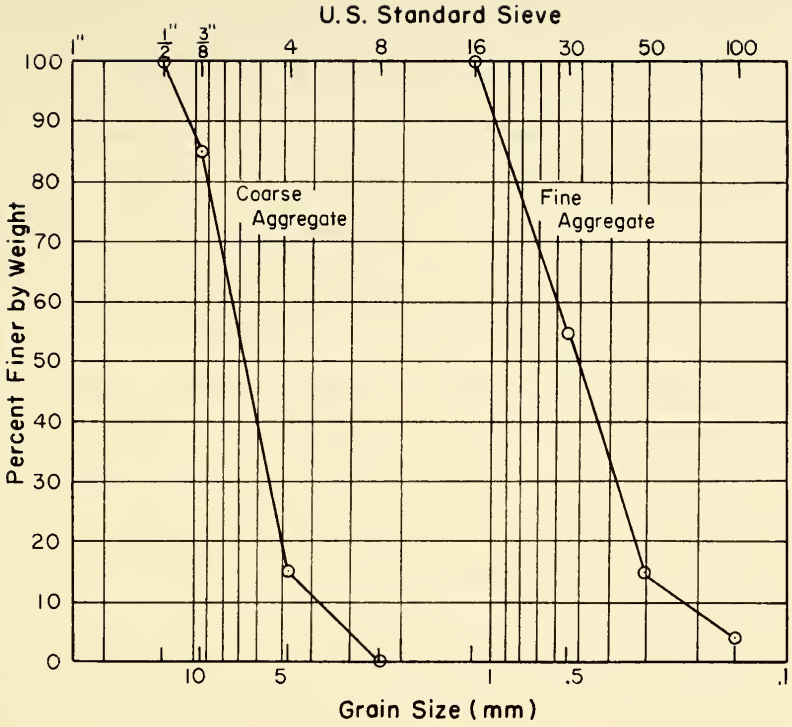

FIG. 12 AGGREGATE GRADATIONS USED IN TEST SPECIMENS

and cured for two days. The cylinders were removed from the molds and placed in a 100°F water bath.

After five days in the hot water bath the cylinders were sliced into disks approximately 3/8 inch thick with a concrete saw. These disks were then ground to the thicknesses desired for the tests on conventional petrographic laps. The first grinding was done with #40 grit abrasive. As the desired thickness was approached, the gritsize was reduced in steps to #120, #400, and #600. The faces of the disks were finished by hand grinding on a glass plate with #1000 grit grinding compound. Care was taken at all stages to insure that the faces of the disks were as nearly plane and parallel as possible. More disks than required were prepared, and the ones with noticeable irregularities or lack of parallelism were set aside to be used as dry weight control specimens. Equal numbers of mortar and concrete disks were prepared.

Prisms for the resistance tests were prepared by cutting the rough 3/8-inch thick disks into prisms approximately 2 inches by 1 inch by 3/8 inch and grinding to final dimensions in a manner similar to that used for the capacitance disks.

All sawing and grinding was done wet with water. The specimens were kept wet at all times and were stored in tap water at room temperature until ready for testing in order to avoid any drying from taking place.

The age of the mortar and the concrete at the time of the beginning of the tests was 28 days.

Test Procedures

To begin the permittivity tests a disk was removed from the water and the free water wiped from its surfaces. The disk was weighed as quickly as possible on a Chainomatic balance to the nearest .001 gm, inserted in the capacitance test cell, and the capacitance bridge was balanced. Each disk had one face and a point on the edge marked so it could be oriented in the capacitor the same way each time. The weight, capacitance, and dissipation factor readings were recorded, and the disk was removed from the cell and placed in an appropriate moisture environment to prepare it for the next reading. This procedure was repeated for each disk.

The same general procedure was followed with the resistance test prisms except that their resistance was measured with the resistance bridge.

Because this study was a part of an investigation to evaluate a method of measuring transient water contents, no effort was made to insure that the specimens obtained equilibrium with their moisture environment before the readings were taken. Drying of the samples was accomplished simply by letting evaporation take place first over water in a dessicator. When this process became slow, evaporation was permitted in the incubator atmosphere which, except for temperature, was approximately the laboratory atmosphere. To establish the curve at low water contents, the samples were heated for brief periods at 60°C, cooled, and tested. Half of the samples were cycled by drying at 60°C and the other half at 105°C. Wetting was by absorption first from the incubator atmosphere and later over water in the dessicator. When higher

water contents were required, the specimens were immersed briefly in distilled water, returned to the saturated atmosphere of the dessicator, and tested after several hours. Finally, the samples were immersed in distilled water for 24 hours. A drying-wetting cycle was usually completed in eight days. The procedure was then repeated through 10 cycles. The specimens were removed periodically from the first, second, third, sixth and tenth cycles, tested, and returned. Measurements were not made during the other cycles. Approximately six points were determined for each drying and wetting phase tested.

After the tenth cycle, all samples were oven dried at 105°C and their dry weights taken. One permittivity and one resistance specimen were immersed in a 1.0 Normal NaCl solution for 24 hours, and measurements were made for one additional drying phase. Also, one permittivity and one resistance specimen which previously had been oven dried to only 60°C were immersed in distilled water for 24 hours, and one additional drying phase was run.

The first two resistance readings during the first drying were made by pressing foam rubber backed foil electrodes to the ends of the specimens. After the second reading, the prisms were dry enough to permit applying silver conductivity paint to the ends of the samples, and subsequent readings were made by clamping the leads to the painted silver electrodes.

Preliminary tests (5) had shown that there is an increase in the oven dry weights of the specimens with each cycle of drying and wetting. This presents no special problem with the samples dried to 105°C because this is the standard reference for water contents and their dry

weight is obtained at the end of each drying phase. Increases can be distributed over the cycle for the purpose of calculating the water content at each test point.

The problem involved with specimens dried only to 60°C was more difficult because the test data did not give any basis for reference to the standard moisture content relative to drying at 105°C. In an effort to provide such a reference, dry weight control specimens were included in the test procedure. These specimens consisted of disks which had been sawed into two approximately equal parts and the two parts of the same disk marked for identification. Four mortar and four concrete disks were prepared in this way for control specimens. One half of each disk was removed from the test at the end of the first drying, and its water content after drying to 60°C was determined by drying to 105°C. The remaining specimens were kept with the 60°C test specimens at all times, and one mortar segment and one concrete segment were removed from the test at the ends of the second, third, sixth, and tenth drying phases to determine their moisture contents relative to 105°C. With this information and assuming that the 60°C dry water content was the same for both halves of a given disk at the end of the first drying, it was possible to calculate the increase in dry weight. This information was used to estimate the rate of increase in dry weight of the 60°C test specimens relative to 105°C.

Calculations

The capacitance bridge readings of capacitance C_{xs} and dissipation factor D_x were series equivalent terms. For convenience this capitance was converted to a parallel equivalent capacitance C_{xp} using the

following equation (1).

$$C_{xp} = \frac{C_{xs}}{1 + D_x^2} \qquad [33]$$

This capacitance and the dissipation factor define a parallel RC circuit electrically equivalent to the circuit connected to the bridge terminals. The circuit seen by the bridge, however, contains not only the capacitance of the specimen being tested but also the capacitance of the leads, the contact capacitance, and the stray and fringe capacitances. Before the dielectric properties of the specimen can be determined, these extraneous effects must be removed.

The dielectrics involved in the leads, contact, and fringe and stray capacitances are either Teflon or air. Both of these are low loss dielectrics, and relative to the sample, their dissipation factors may be assumed zero. Making this assumption and using Equations 34 and 35 (39), a new parallel RC circuit can be calculated equivalent to the specimen and the contact with all other factors removed as indicated schematically on Figure 13.

$$C_b = C_{xp} - C_l - C_f \qquad [34]$$

$$R_b = \frac{1}{\omega C_{xp} D_x} \qquad [35]$$

C_b and R_b are referred to as the apparent capacitance and apparent resistance, respectively.

Writing the expression for the impedence of the left hand circuit of Figure 13 and setting it equal to the impedence of the right hand circuit:

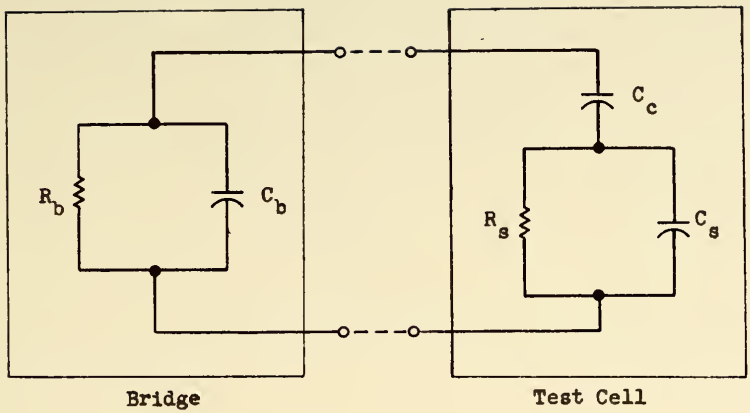

Fig. 13. Equivalent Reduced Test Circuits.

$$\frac{R_b(1 - j\omega C_b R_b}{1 + (\omega C_b R_b)^2} = \frac{R_s(1 - j\omega C_s R_s)}{1 + (\omega C_b R_b)^2} = \frac{j}{\omega C_c} \qquad [36]$$

Equating the real parts

$$\frac{R_b}{(1 + (\omega C_b R_b)^2} = \frac{R_s}{(1 + \omega C_s R_s)^2} \qquad [37]$$

and the imaginary parts

$$\frac{\omega C_b R_b^2}{1 + (\omega C_b R_b)^2} = \frac{\omega C_s R_s}{1 + (\omega C_s R_s)^2} + \frac{1}{\omega C_c} \quad . \qquad [38]$$

Simultaneous solution of Equations 37 and 38 yields the capacitance C_s and the equivalent parallel resistance R_s of the specimen. Then the

relative dielectric constant κ' of the specimen may be found from Equation 1

$$\kappa' = \frac{C_s}{C_o} \qquad [39]$$

and the dielectric conductivity may be calculated from Equation 20

$$\sigma = \frac{\epsilon_o}{R_s C_o} \qquad [40]$$

which for a parallel plate capacitor of area A and distance between plates of L becomes

$$\sigma = \frac{L}{R_s A} \quad . \qquad [41]$$

The dielectric conductivities of the resistance test specimens are calculated directly from the measured data using this latter equation without the need for any preliminary calculations since R_s is measured directly.

To avoid the necessity of a numerical solution of Equations 37 and 38 for each set of data, these equations were solved on an electronic computer for appropriate values of C_c and curves similar to Figure 14 plotted. These curves permit a graphical solution for C_s and R_s and save a great deal of time in the analysis of the data. It is apparent from this set of curves that as R_s becomes small the method loses its precision, and for very low values of R_s it is impossible to even estimate C_s. This is true not only of the graphical solution but also of the numerical solution because for small values of R_s very small errors in R_b, C_b, and C_c can cause very large errors in C_s and therefore in κ'. The determination of R_s is not as critically sensitive to these errors as the determination of C_s.

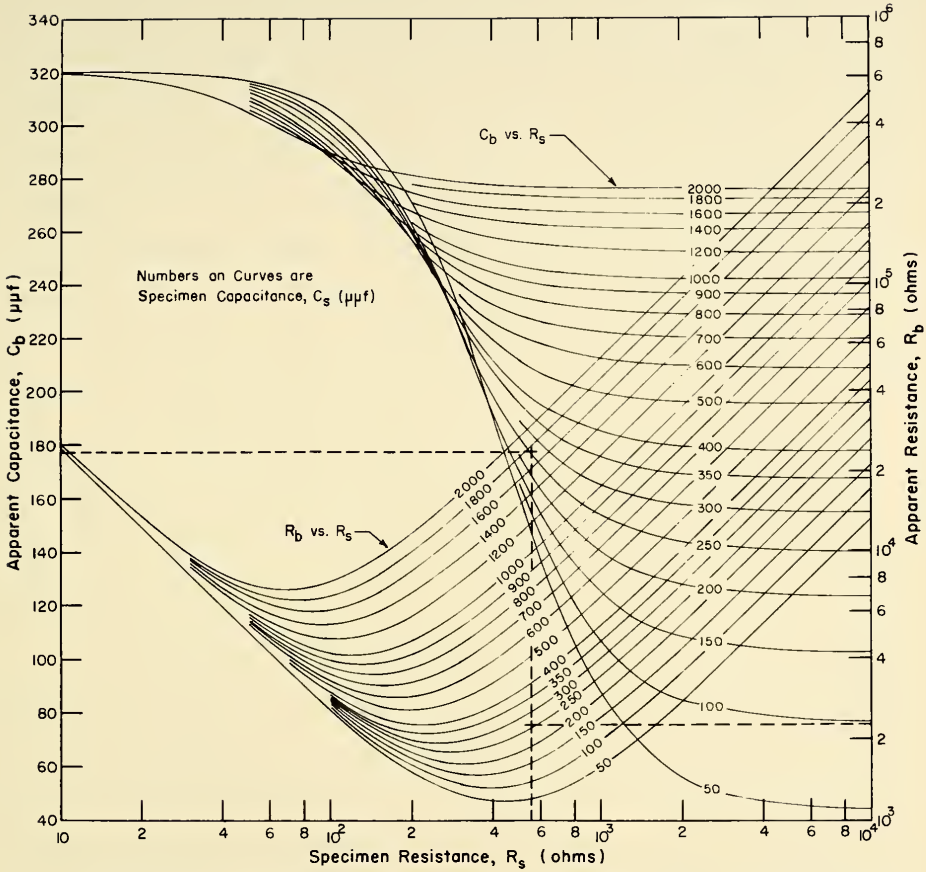

FIG. 14 GRAPH FOR DETERMINATION OF SPECIMEN CAPACITANCE AND RESISTANCE FROM APPARENT CAPACITANCE AND RESISTANCE FOR A CONTACT CAPACITANCE OF 320 $\mu\mu f$ AND A FREQUENCY OF 10^6 cps

Before these calculations can be made, it is necessary to know the contact capacitance C_c. Possibilities for its determination are direct calculation from its geometry and the dielectric constant of Teflon or by direct measurement with the test capacitor plates clamped together. These methods, however, neglect the effects of irregularities in the surfaces of the disks and the resulting air spaces between the specimens and the capacitor plates. For the tests in this study C_c was estimated from the test data itself. All of the permittivity specimens tested were so proportioned that at the high water contents for the first cycle R_s was sufficiently low that the corresponding values of C_b approached the values of C_c for the respective disks. Therefore, C_c was estimated by plotting the C_b-water content curve and approximating the asymptote of this curve at the high water content end, and the C_b value of this asymptote was assumed equal to C_c (See for example Figure 17).

To check the calculation procedure and equipment constants, tests were run on liquids of known dielectric constant. The liquids were held in the capacitance test cell by a thin Teflon ring cemented to the lower plate. C_c was estimated by reducing the resistance of water in the cell by adding NaCl until C_b approached a constant value. This value was taken as the contact capacitance with liquids in the cell. The capacitances of five liquids of known dielectric constant (Table 1) were tested and their dielectric constant calculated. The known values are compared with the measured values on Figure 15. All of these liquids had relatively low loss angles. To check the method for high loss materials, water with various NaCl concentrations was tested, and R_b and C_b

TABLE 1. Relative Dielectric Constants of Liquids Tested to Evaluate Equipment and Procedures.

No.	Liquid	Dielectric Constant at 30°C *
1	Carbon Tetrachloride	2.2
2	Chlorobenzene	5.5
3	1, 2-Dichloroethane	10.1
4	Methanol	31.6
5	Water	76.7

* Data from National Bureau of Standards (25).

were calculated. R_s was obtained from measured values of R_b and the theoretical R_b - R_s curve calculated for the dielectric constant of distilled water and the geometric capacitance of the test cell. C_b was plotted with respect to these values of R_s. Figure 16 shows the correspondence between the measured C_s - R_s relationship and the theoretical relationship, assuming the dielectric constant of water is independent of its salt concentration. The conclusions derived from these tests were that the calibration and calculation methods were sufficiently accurate for the purposes of these studies and that the dielectric constant of bulk water is not greatly affected by its salt concentration at least up to a concentration of about 1.0 Normal for NaCl. As expected, there is considerable scatter at very high conductivities, and in this range little can be said about the accuracy of the procedure.

A set of sample calculations for relative dielectric constant and dielectric conductivity from the permittivity test data is included in Appendix 1.

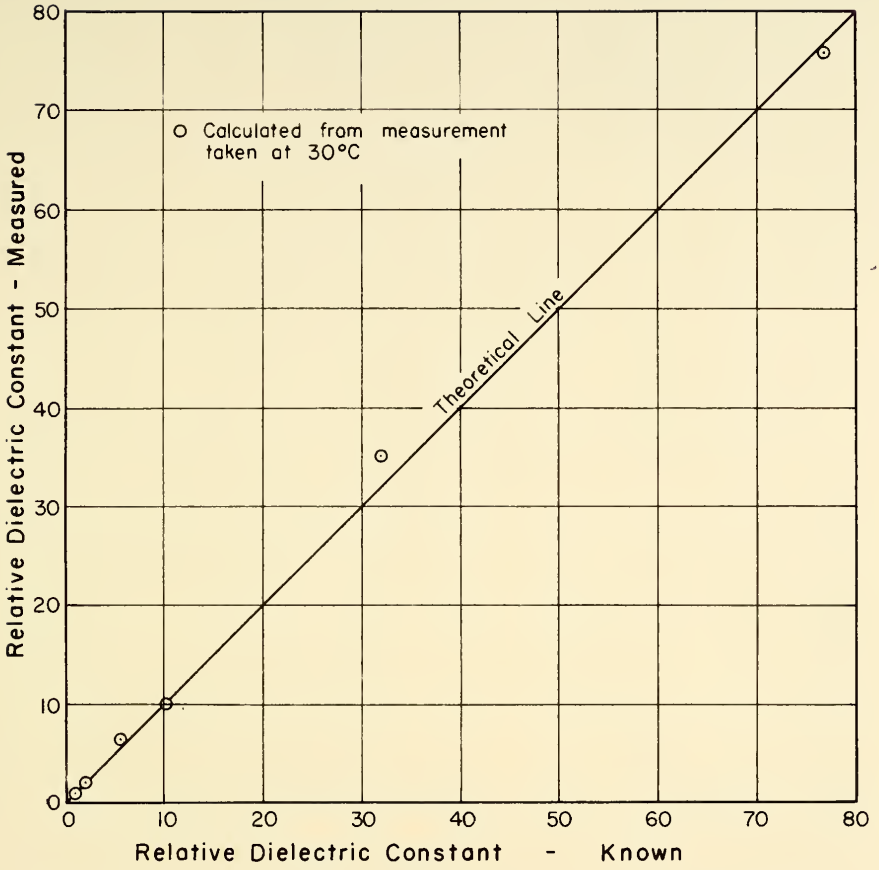

FIG. 15 MEASURED VS. KNOWN RELATIVE DIELECTRIC CONSTANT FOR STANDARD LIQUIDS

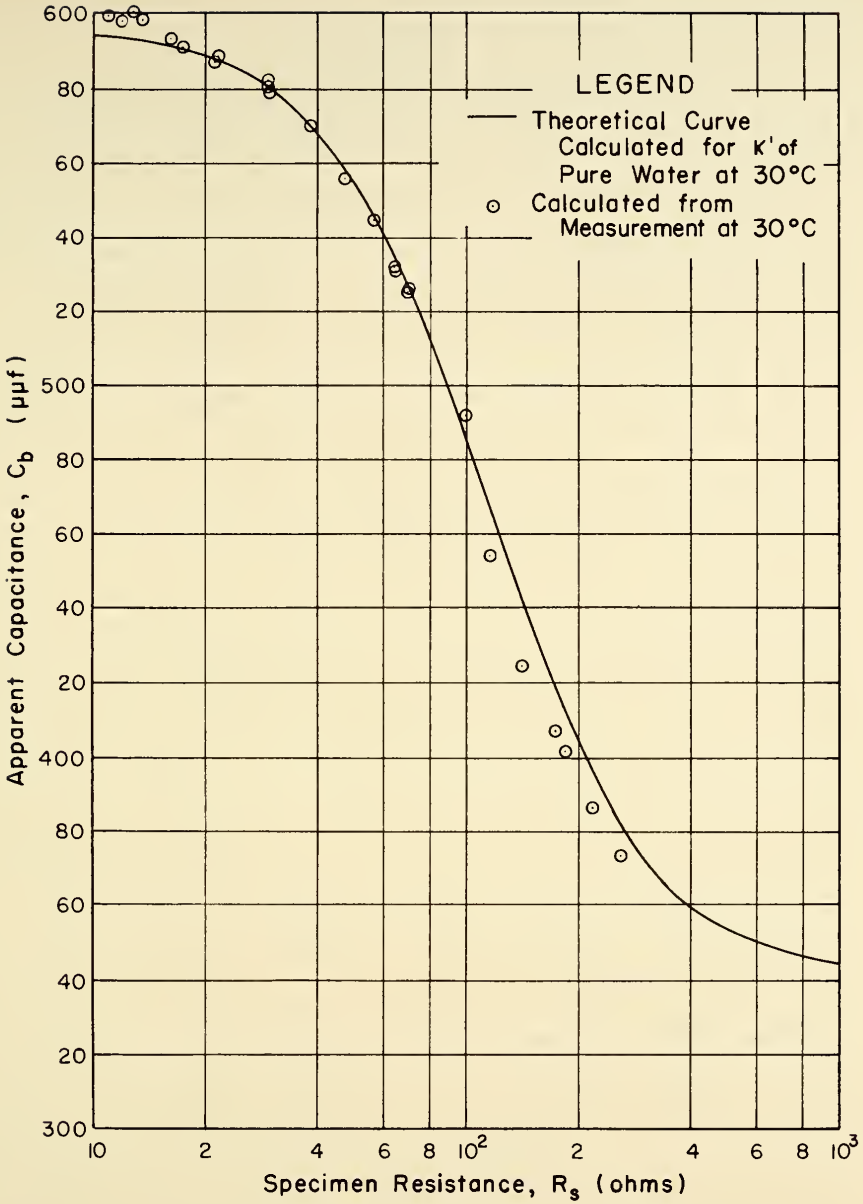

FIG. 16 MEASURED AND THEORETICAL APPARENT CAPACITANCE VS. SPECIMEN RESISTANCE RELATIONSHIPS FOR NaCl-WATER SOLUTION

Test Results

Permittivity tests were conducted on eight specimens at a frequency of 10^6 cps, and resistance tests were conducted on four specimens at a frequency of 10 cps. The test specimens are identified, and their pertinent characteristics and test conditions are listed in Table 2.

Apparent capacitance (C_b)-water content relationships typical of the permittivity tests are given as Figures 17 and 18. These figures show the measured capacitances with the effects of leads and stray capacitances removed but without taking into consideration the contact capacitances. Specimen C-1 (Figure 17) was a thin disk and was oven dried to 105°C. These conditions caused a continuous shifting of the apparent capacitance-water content curves for successive cycles, and Figure 17 is typical of the results obtained from tests of this type. The effect of adding salts to the pore fluid is also shown on this figure. Specimen CT-2 (Figure 18) was a thicker disk dried only to 60°C, and the data in Figure 18 is representative of the test conditions which resulted in the most consistent results.

Curves representing the various drying and wetting phases have been drawn on Figure 17. On Figure 18 where the spread of the data is less, envelopes to the test data were drawn to delineate the range in water content for which the same capacitance reading could be obtained. In order not to obscure the test data, the results are presented simply as plots of the test points on all other figures.

The results of the low frequency resistance tests are plotted in Figures 19-22. The 10^6 cps dielectric conductivity and relative dielectric constant-water content relationships, as calculated from the permittivity tests are presented in Figures 23-30 and 31-38, respectively.

TABLE +. Identification and Characteristics of Test Specimens

Permittivity Test Specimens

Material	Drying Temp. (°C)	Sample No.	Thickness (cm.)	C_o (μμf)	C_c (μμf)	L/A (cm^{-1})	Notes
Concrete	105	C-1	.399	9.9	300	.0090	*
		CT-1	.668	5.9	320	.0149	
	60	C-2	.396	10.0	305	.0089	**
		CT-2	.653	6.0	320	.0146	
Mortar	105	M-1	.391	10.1	305	.0088	
		MT-1	.665	5.9	330	.0149	
	60	M-2	.404	9.8	320	.0090	
		MT-2	.681	5.8	340	.0152	

Resistance Test Specimens

Material	Drying Temp. (°C)	Sample No.	Thickness (cm.)	L/A (cm^{-1})	Notes
Concrete	105	RC-1	.762	2.91	*
	60	RC-2	.770	2.91	**
Mortar	105	RM-1	.663	3.13	
	60	RM-2	.653	3.35	

* Eleventh drying phase after saturation with 1.0 Normal NaCl solution.

** Eleventh drying phase after 105°C drying

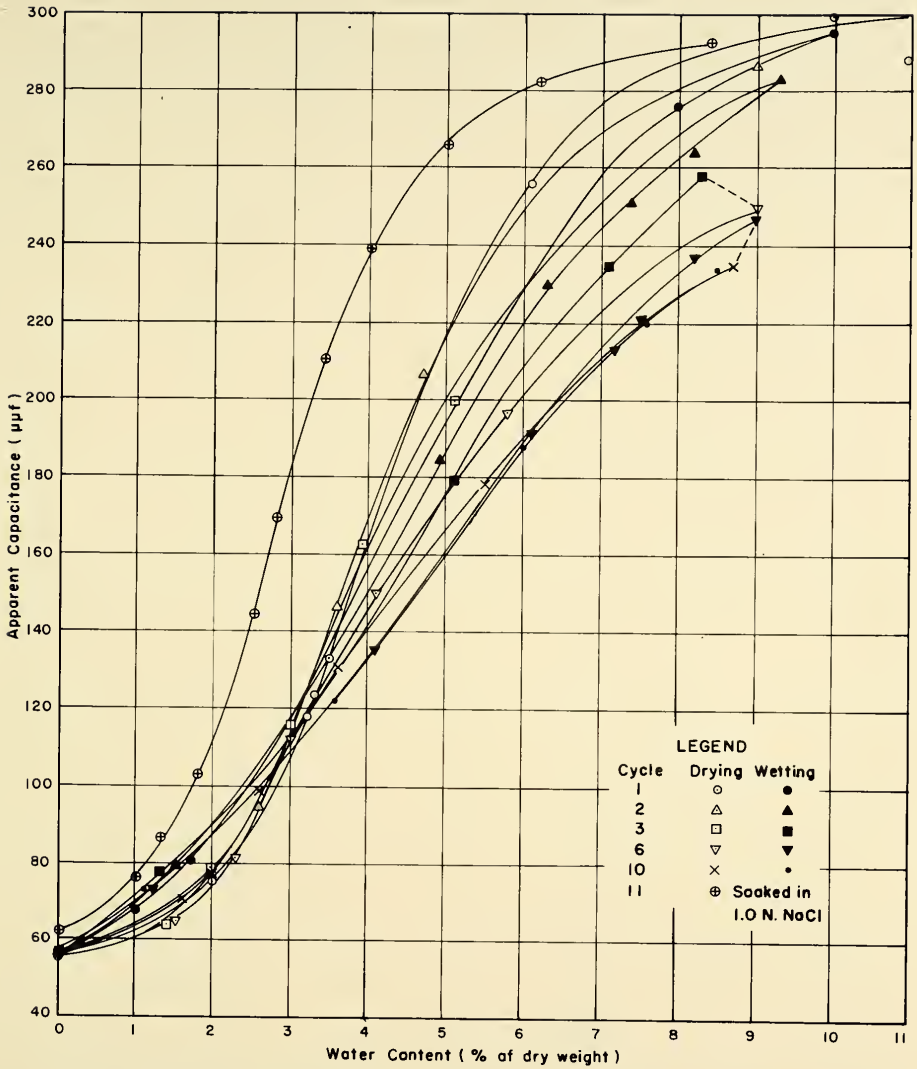

FIG. 17 APPARENT CAPACITANCE AT 10^6 cps VS. WATER CONTENT FOR DISK C-1

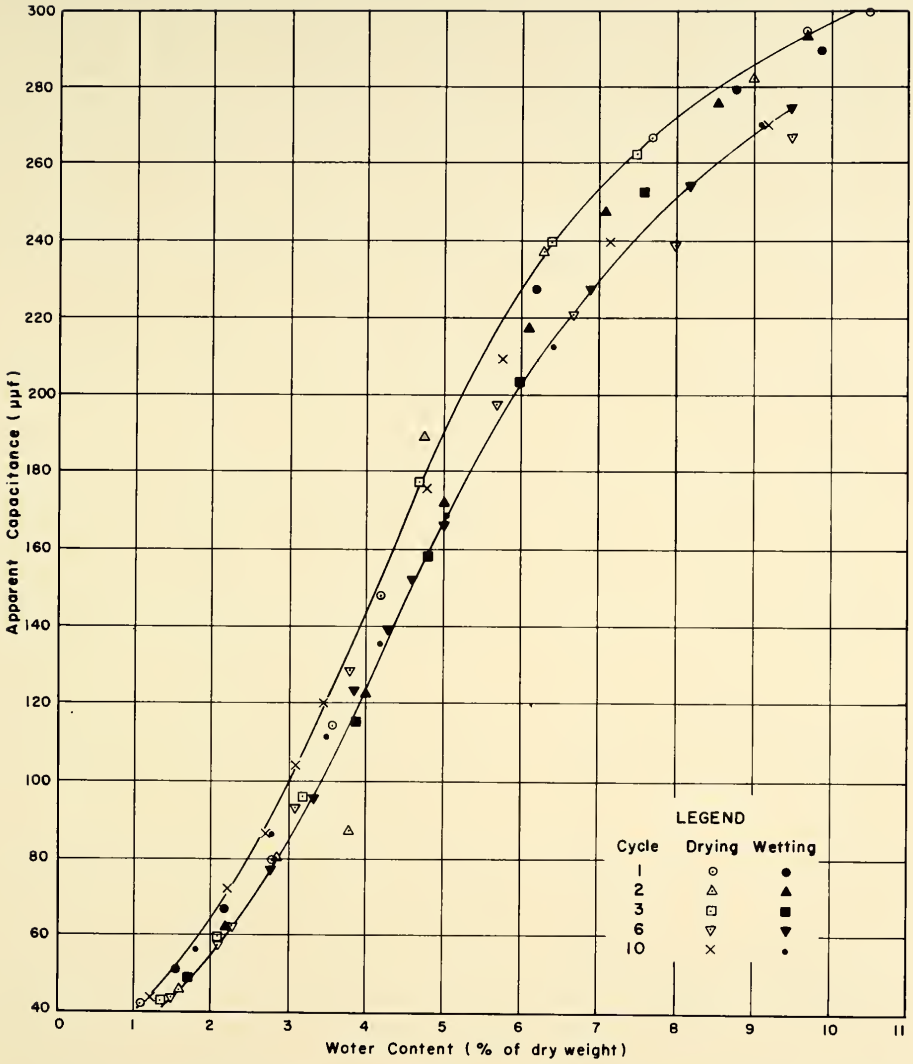

FIG. 18 APPARENT CAPACITANCE AT 10^6 cps VS. WATER CONTENT FOR DISK CT-2

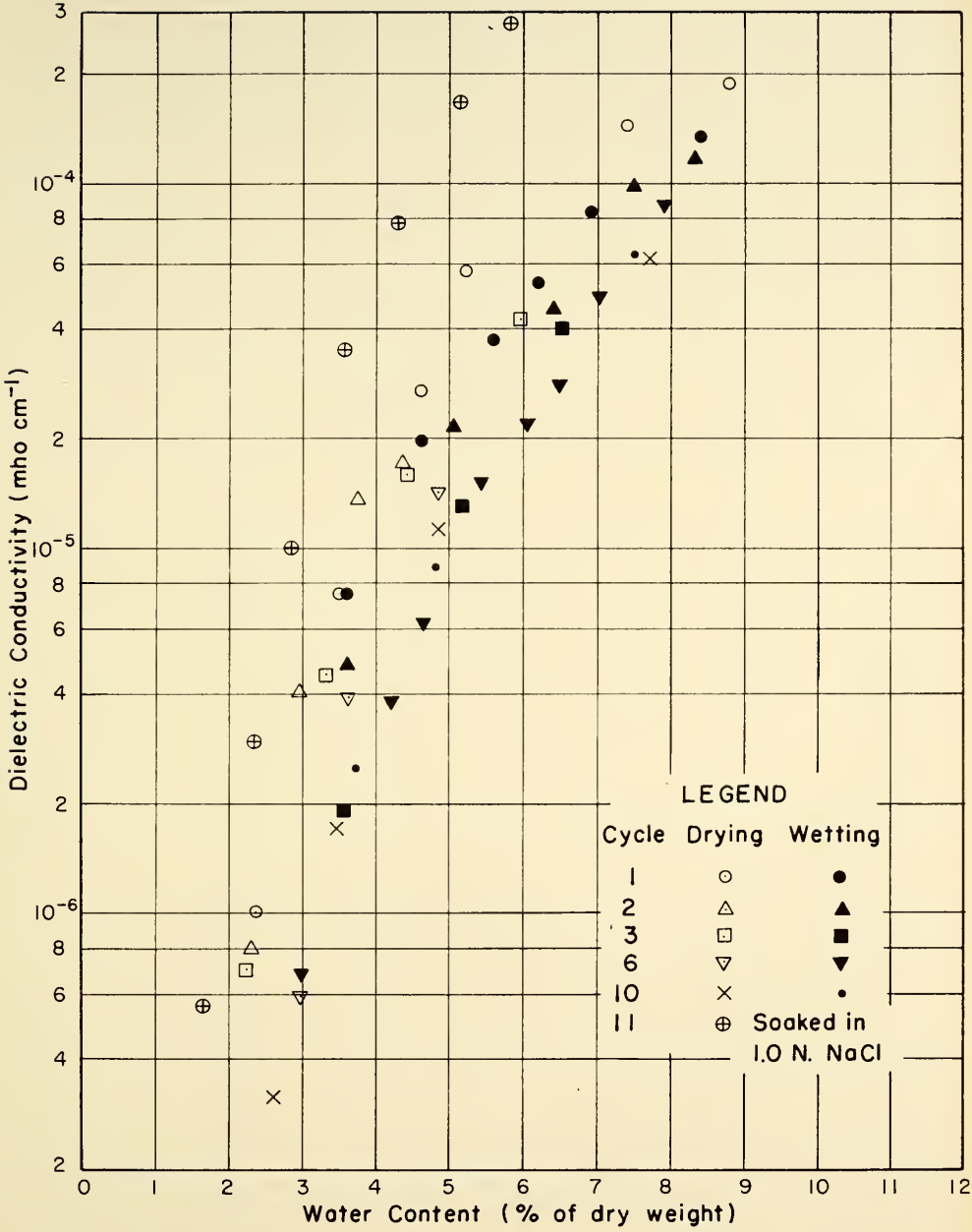

FIG. 19 DIELECTRIC CONDUCTIVITY AT 10 cps VS. WATER CONTENT FOR SAMPLE RC-1

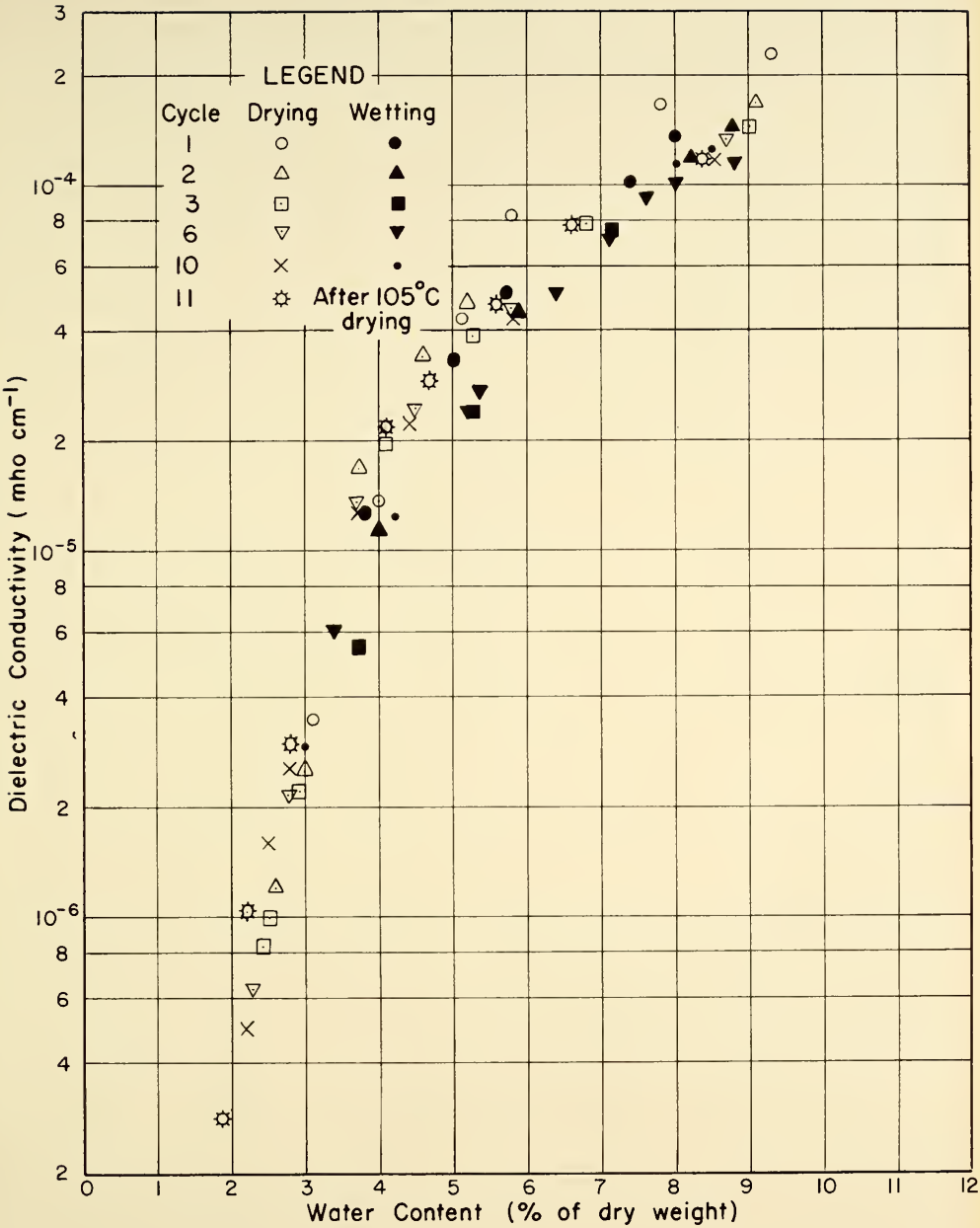

FIG. 20 DIELECTRIC CONDUCTIVITY AT 10 cps VS. WATER CONTENT FOR SAMPLE RC-2

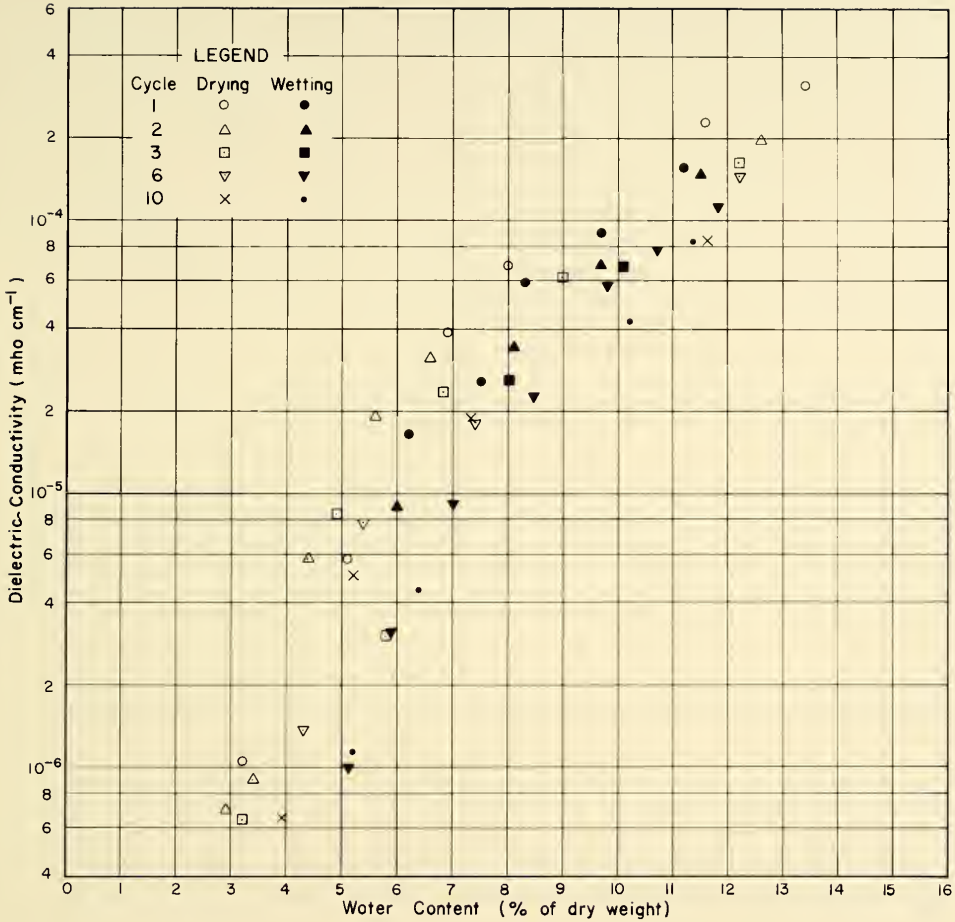

FIG. 21 DIELECTRIC CONDUCTIVITY AT 10 cps VS. WATER CONTENT FOR SAMPLE RM-1

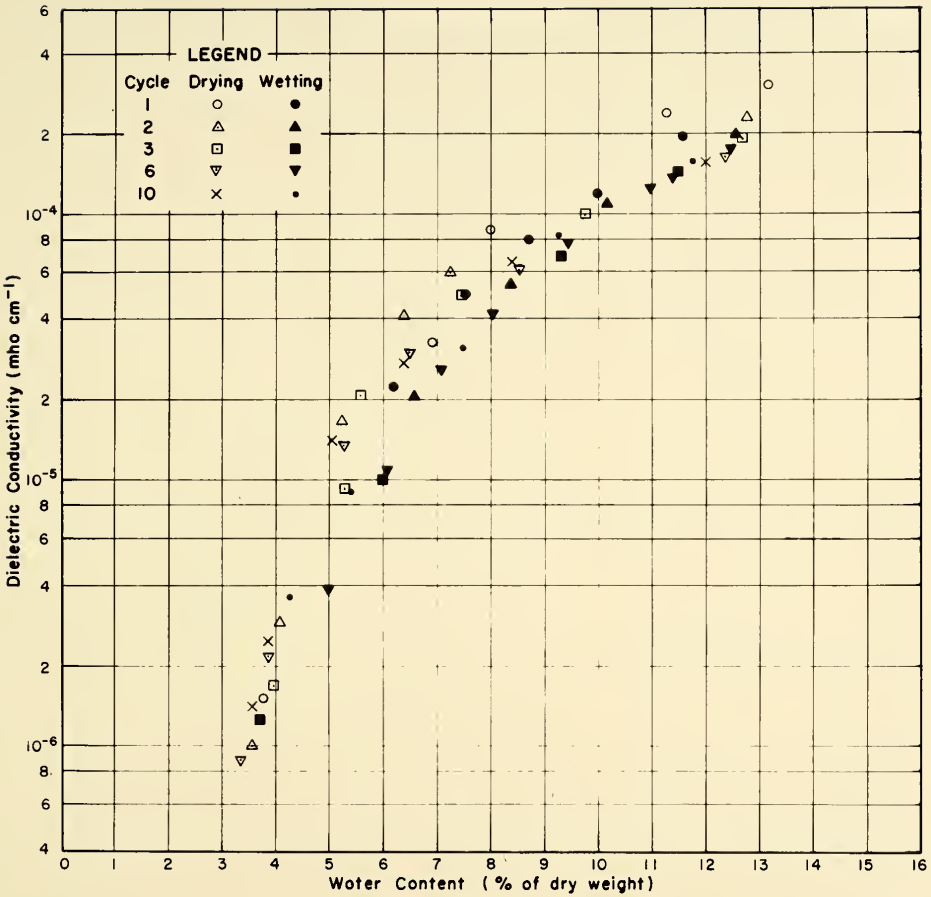

FIG. 22 DIELECTRIC CONDUCTIVITY AT 10 cps VS. WATER CONTENT FOR SAMPLE RM-2

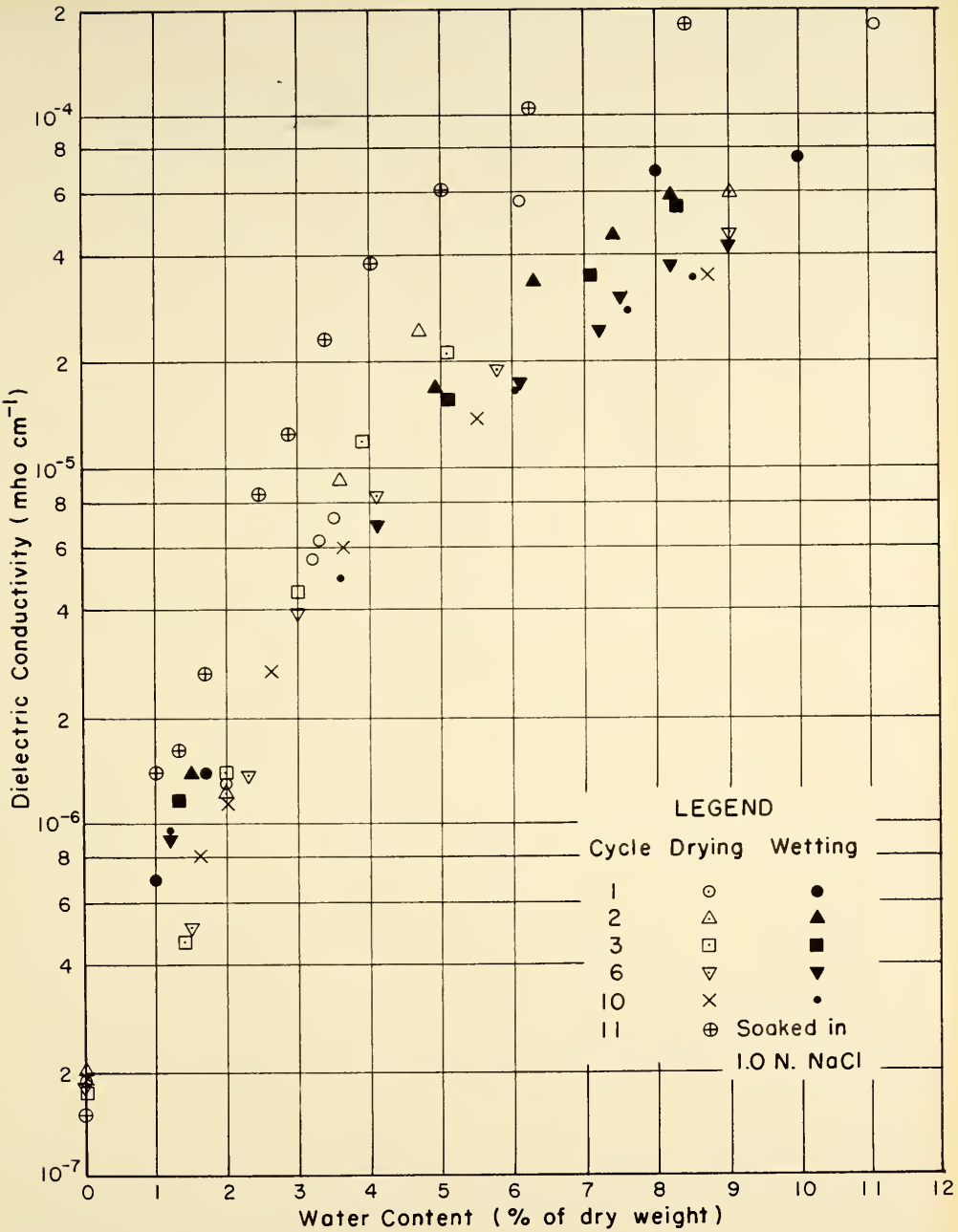

FIG. 23 DIELECTRIC CONDUCTIVITY AT 10^6 cps VS. WATER CONTENT FOR DISK C-1

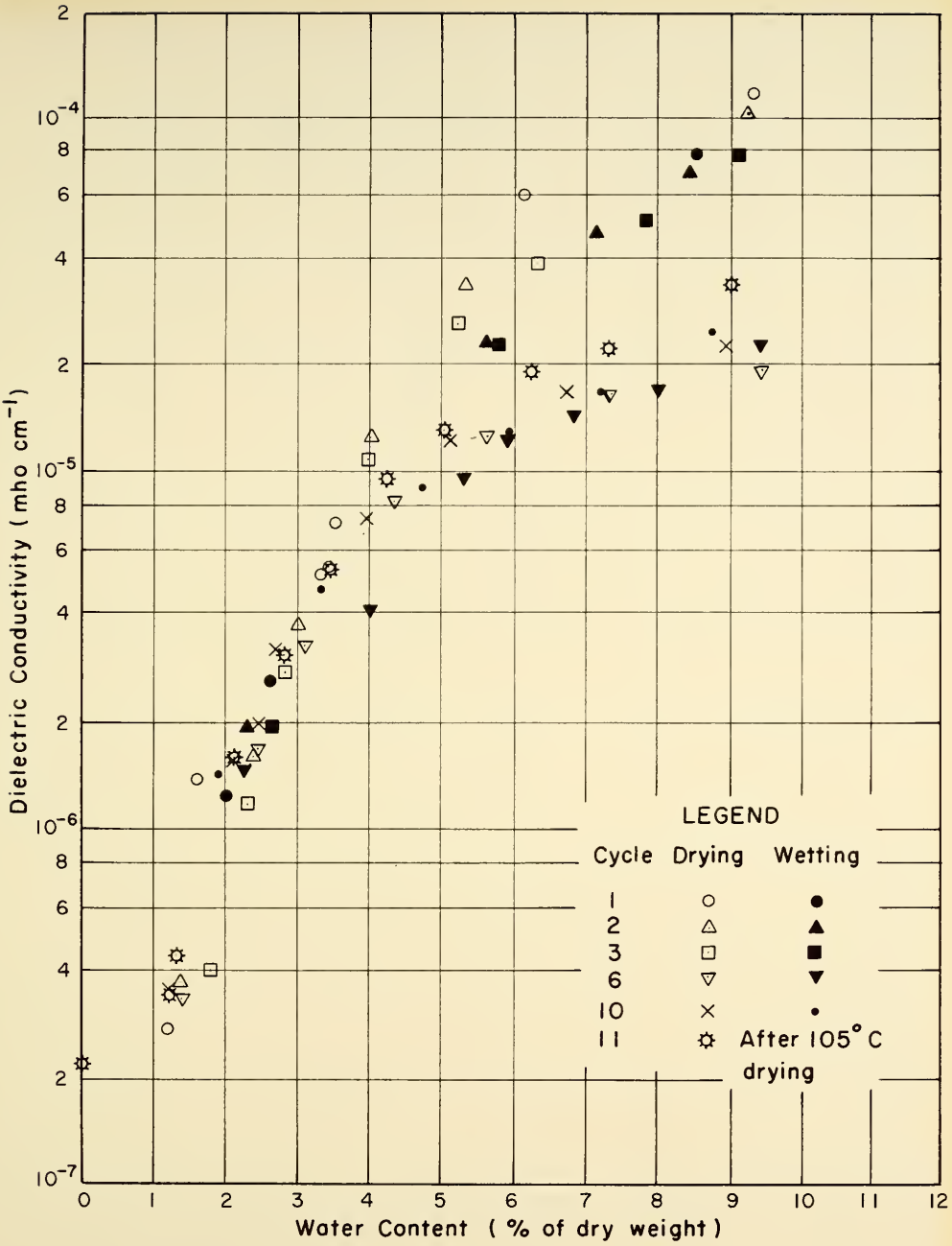

FIG. 24 DIELECTRIC CONDUCTIVITY AT 10^6 cps VS. WATER CONTENT FOR DISK C-2

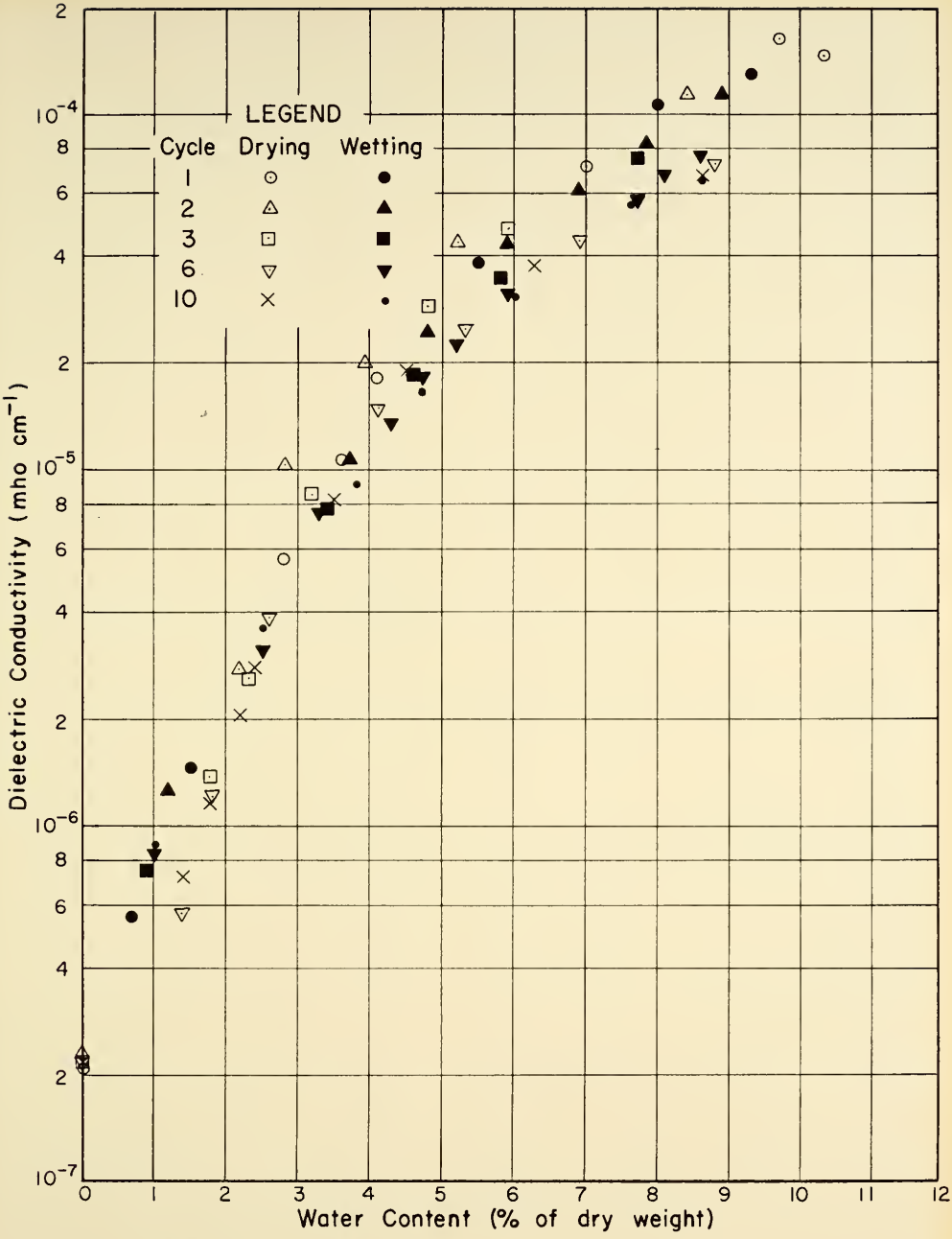

FIG. 25 DIELECTRIC CONDUCTIVITY AT 10^6 cps VS. WATER CONTENT FOR DISK CT-1

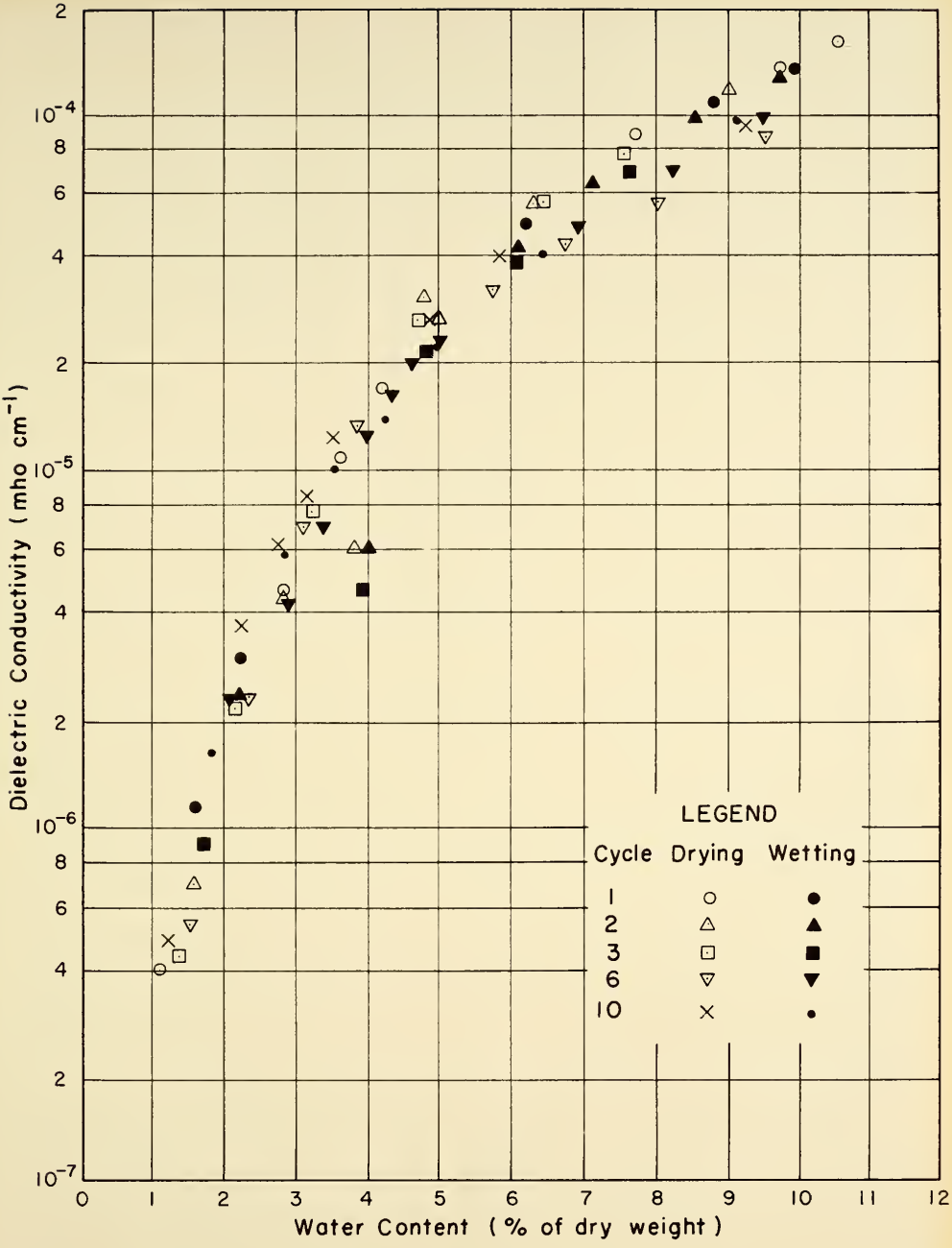

FIG. 26 DIELECTRIC CONDUCTIVITY AT 10^6 cps VS. WATER CONTENT FOR DISK CT-2

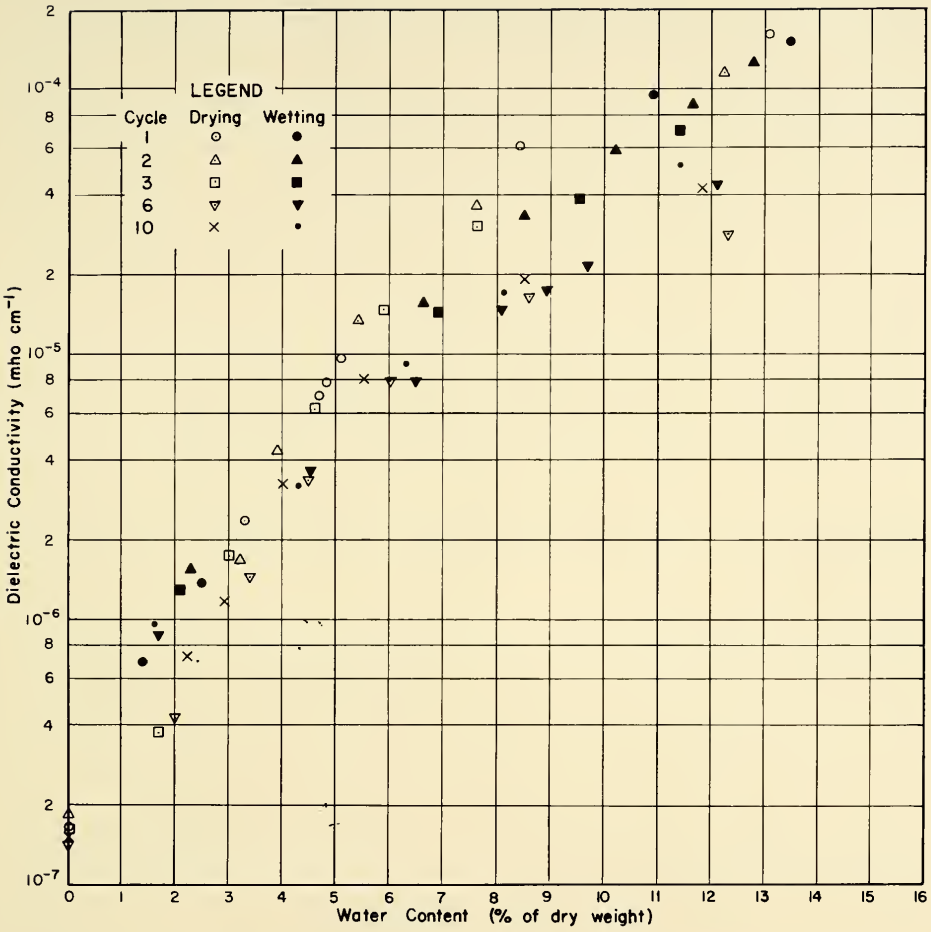

FIG. 27 DIELECTRIC CONDUCTIVITY AT 10^6 cps VS. WATER CONTENT FOR DISK M-1

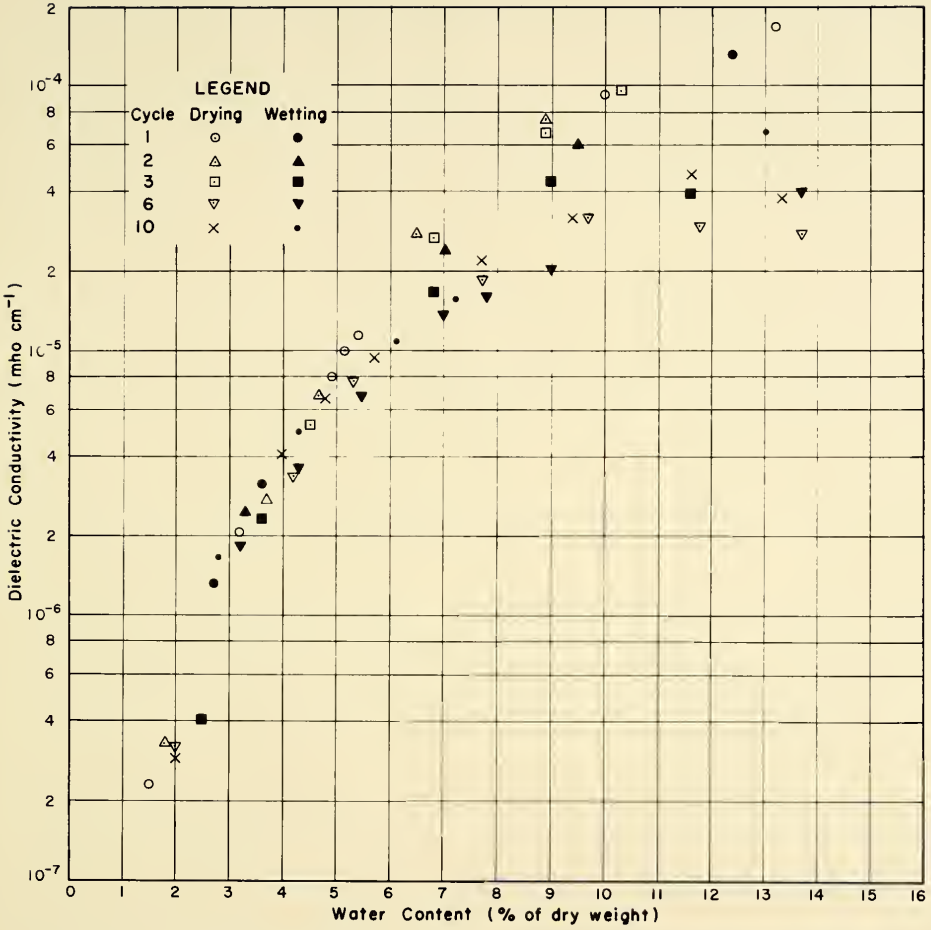

FIG. 28 DIELECTRIC CONDUCTIVITY AT 10^6 cps VS. WATER CONTENT FOR DISK M-2

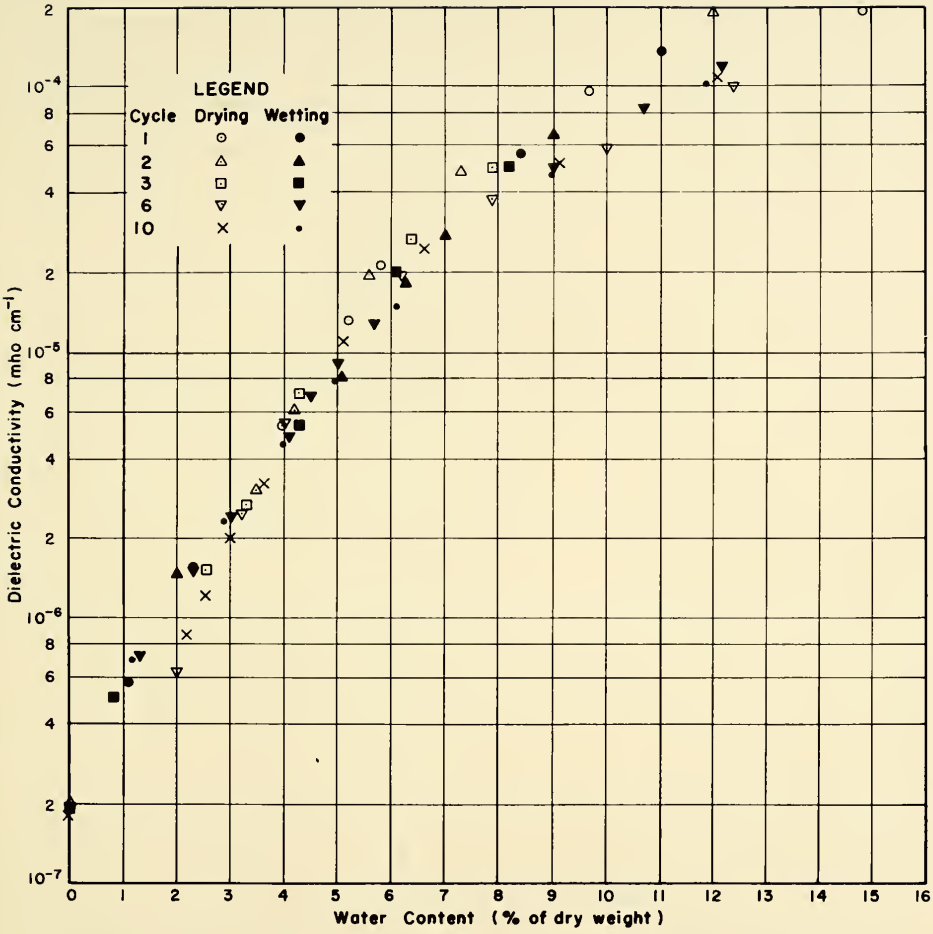

FIG. 29 DIELECTRIC CONDUCTIVITY AT 10^6 cps VS. WATER CONTENT FOR DISK MT-1

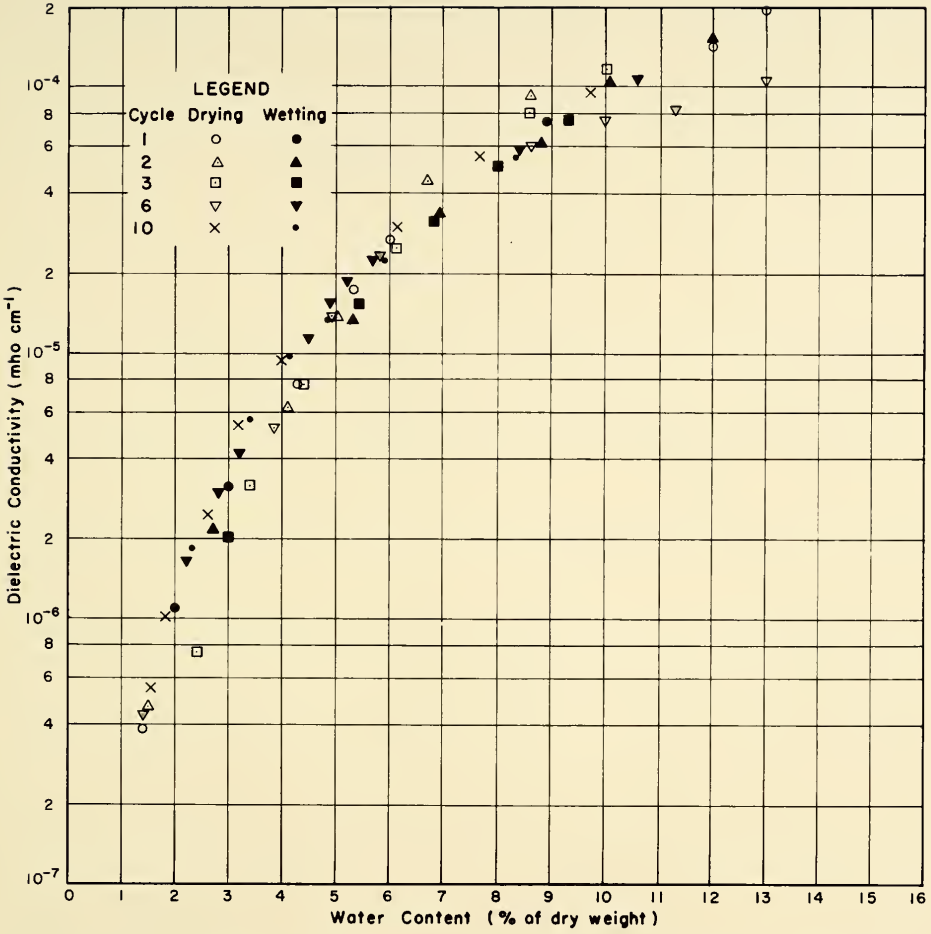

FIG. 30 DIELECTRIC CONDUCTIVITY AT 10^6 cps VS. WATER CONTENT FOR DISK MT-2

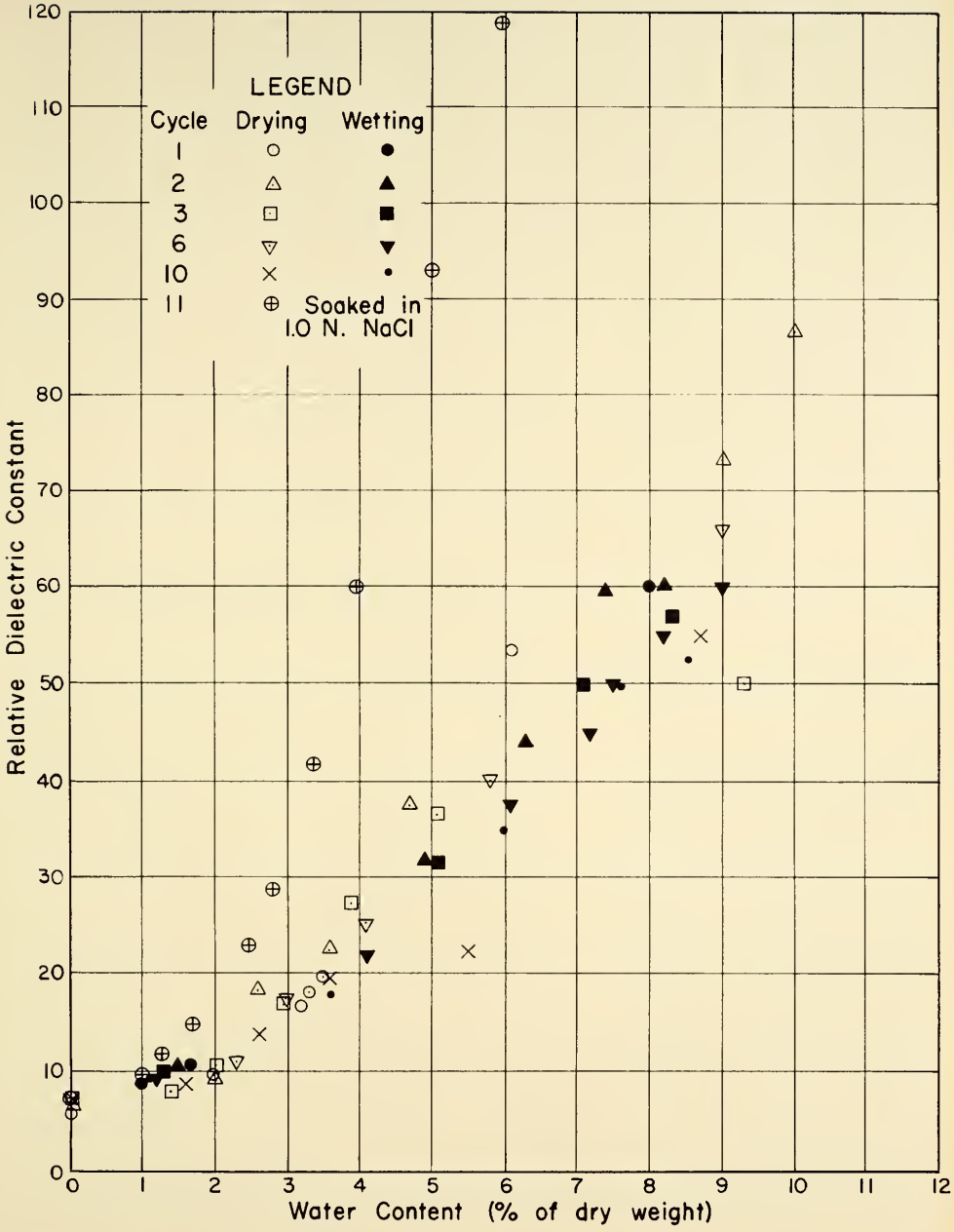

FIG. 31 RELATIVE DIELECTRIC CONSTANT AT 10^6 cps VS. WATER CONTENT FOR DISK C-1

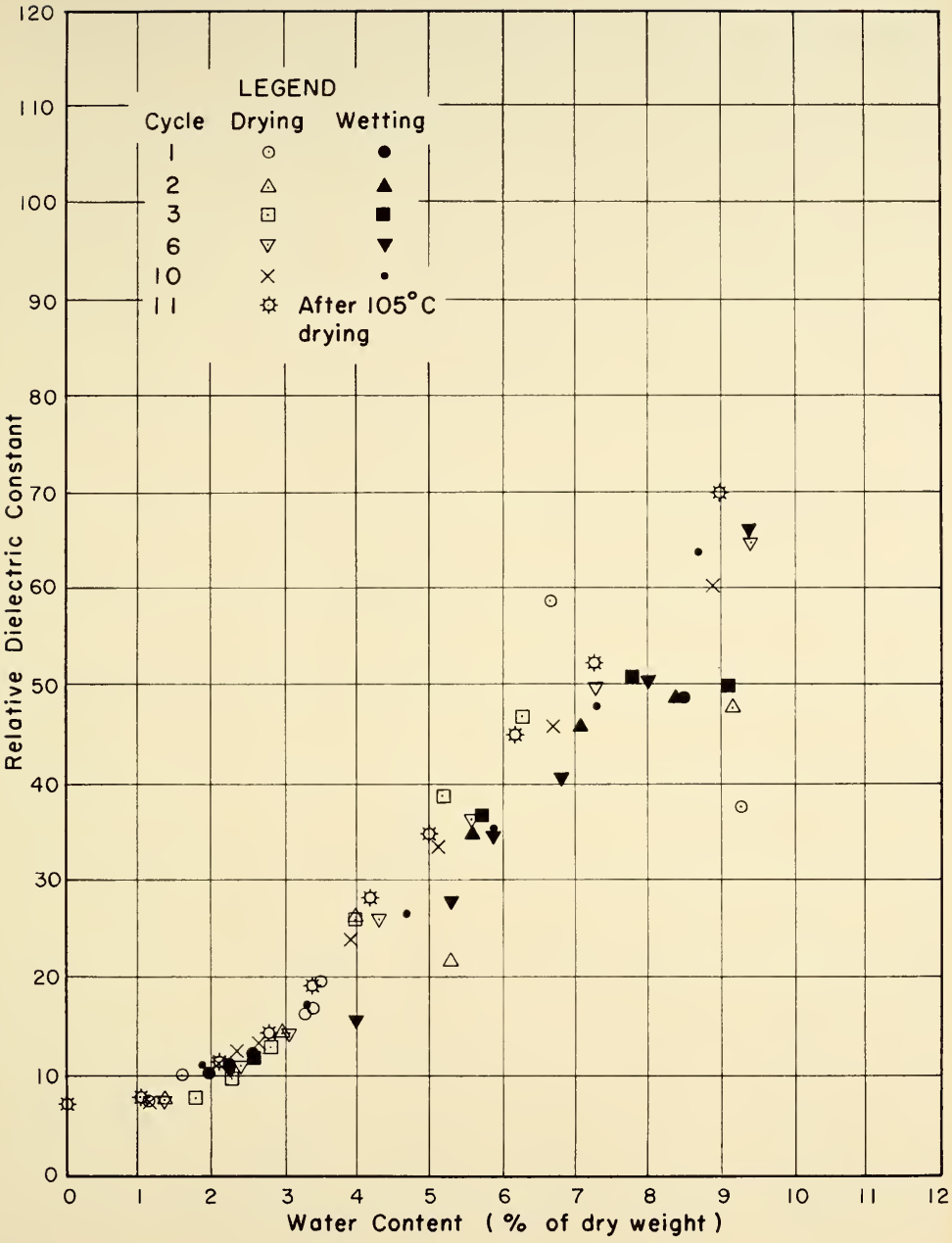

FIG. 32 RELATIVE DIELECTRIC CONSTANT AT 10^6 cps VS. WATER CONTENT FOR DISK C-2

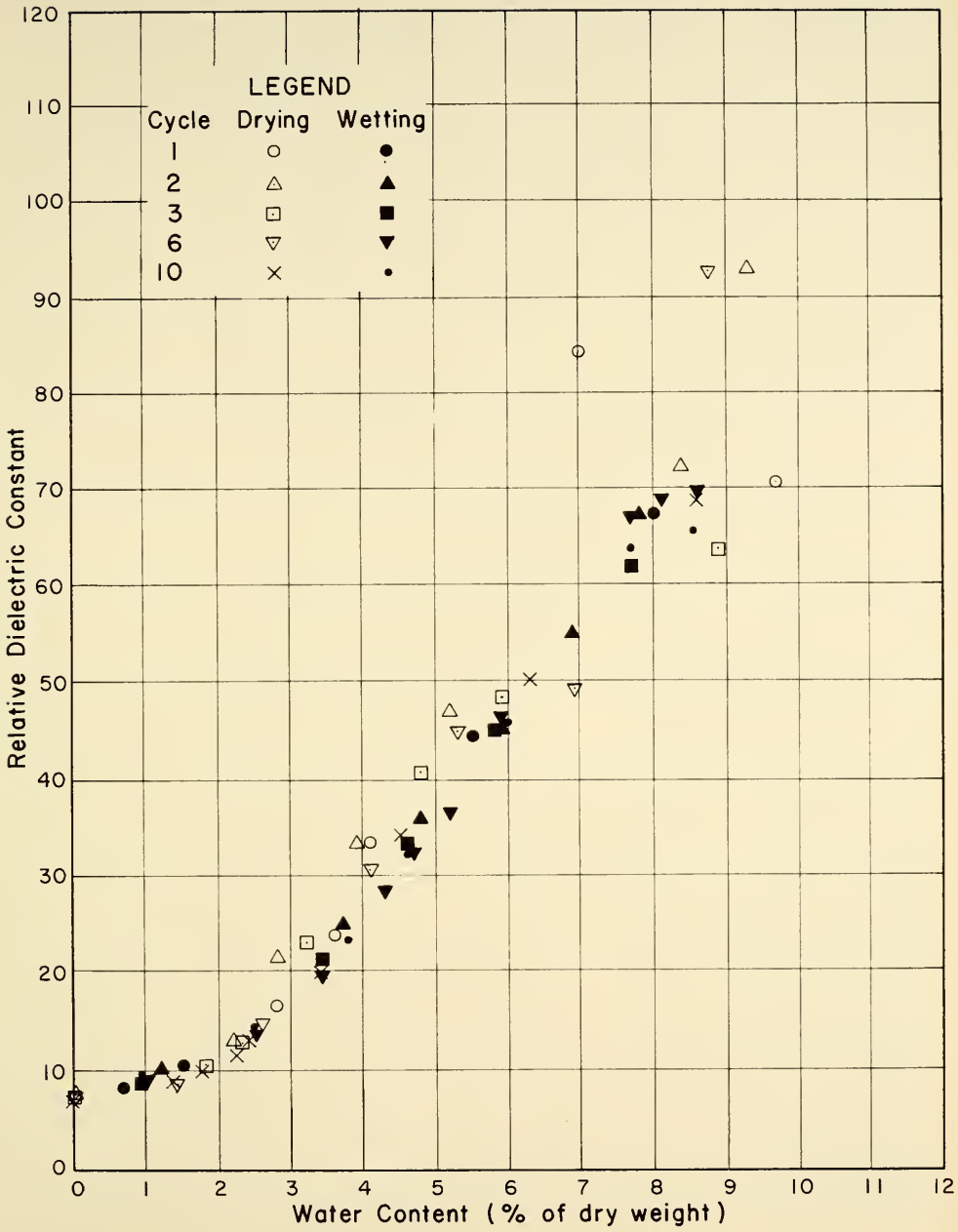

FIG. 33 RELATIVE DIELECTRIC CONSTANT AT 10^6 cps VS. WATER CONTENT FOR DISK CT-1

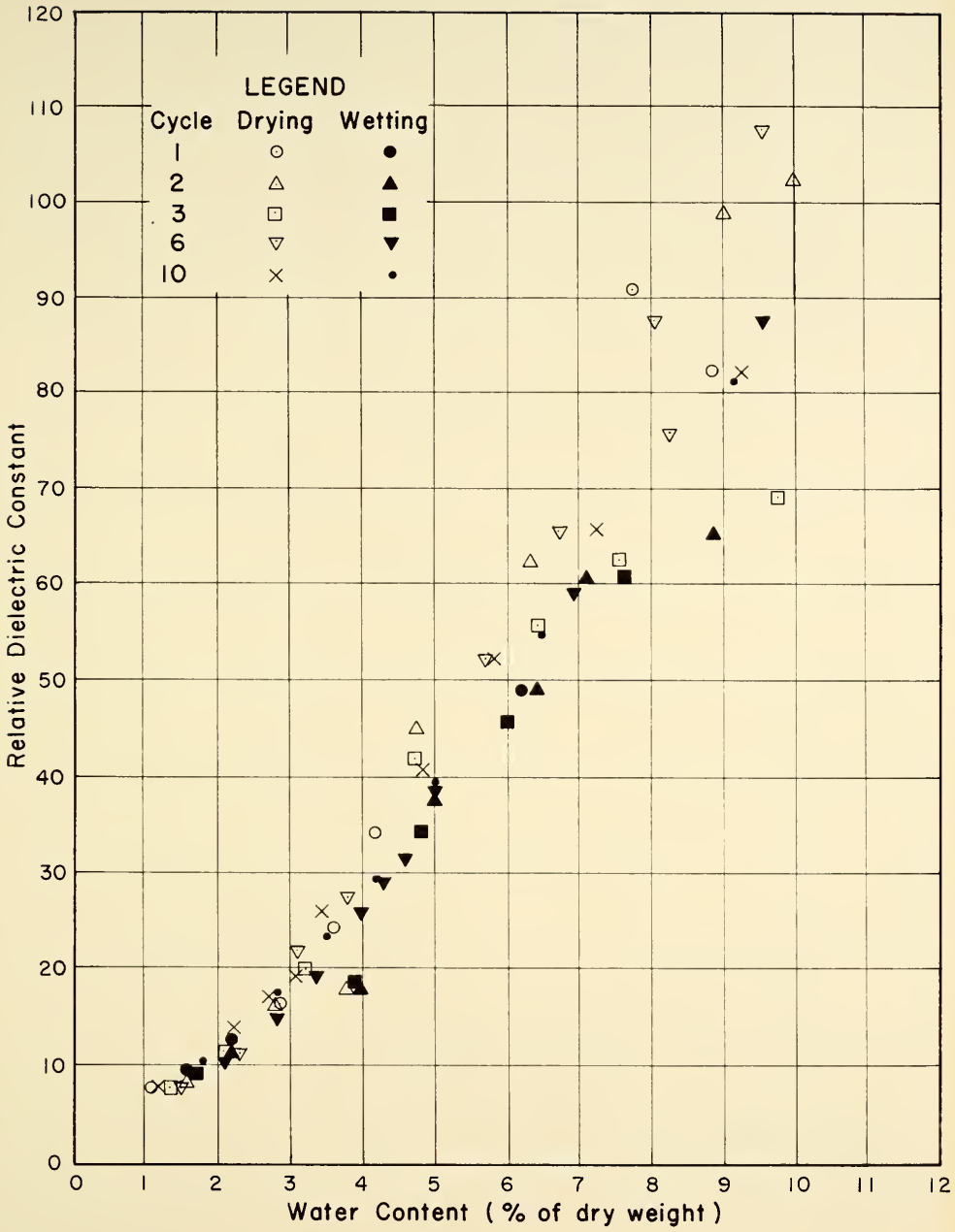

FIG. 34 RELATIVE DIELECTRIC CONSTANT AT 10^6 cps VS. WATER CONTENT FOR DISK CT-2

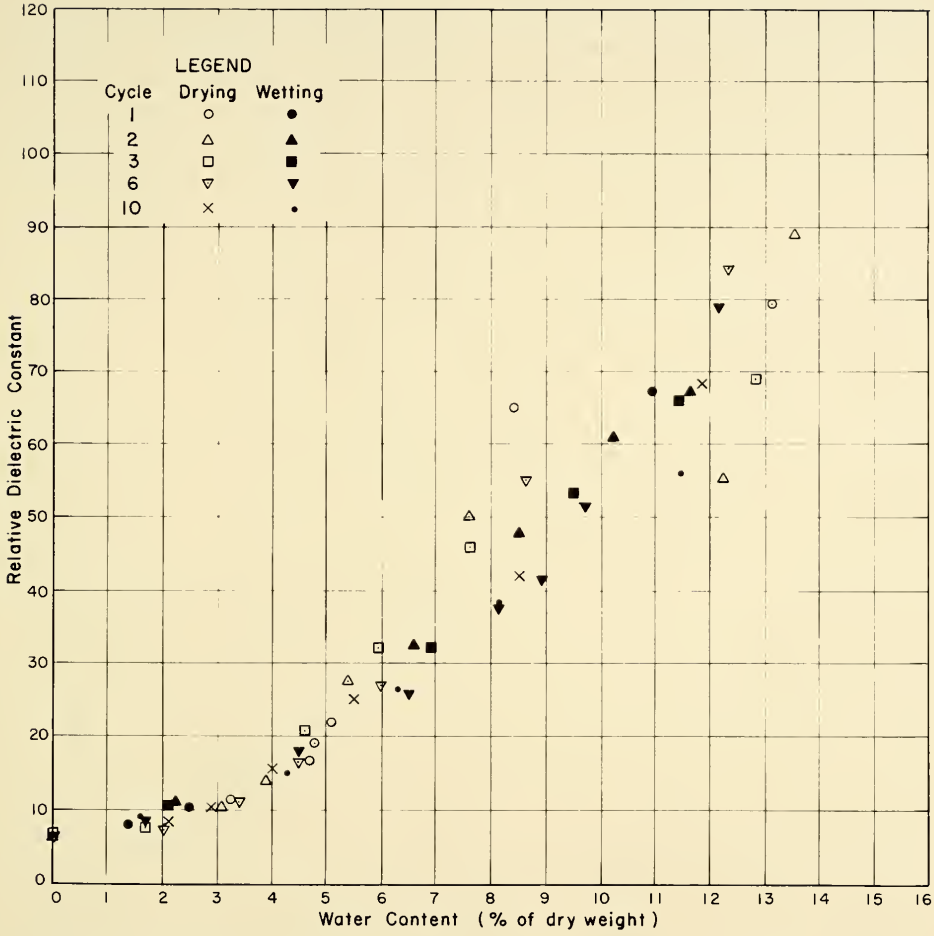

FIG. 35 RELATIVE DIELECTRIC CONSTANT AT 10^6 cps VS. WATER CONTENT FOR DISK M-1

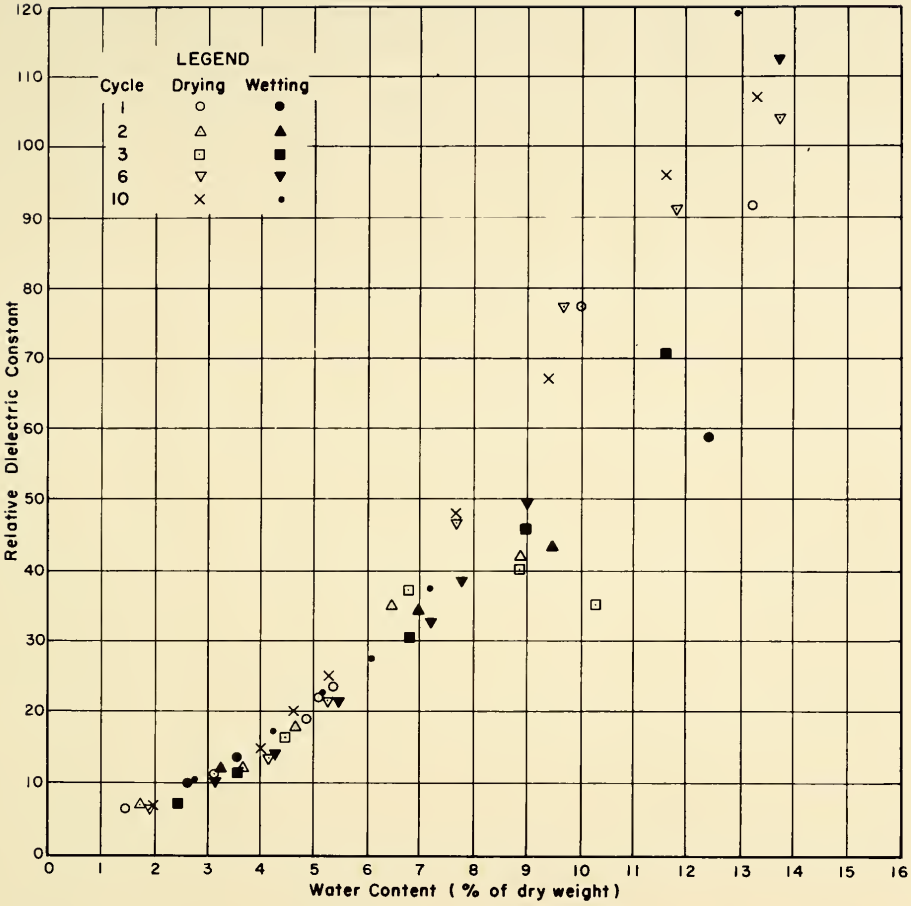

FIG. 36 RELATIVE DIELECTRIC CONSTANT AT 10^6 cps VS. WATER CONTENT FOR DISK M-2

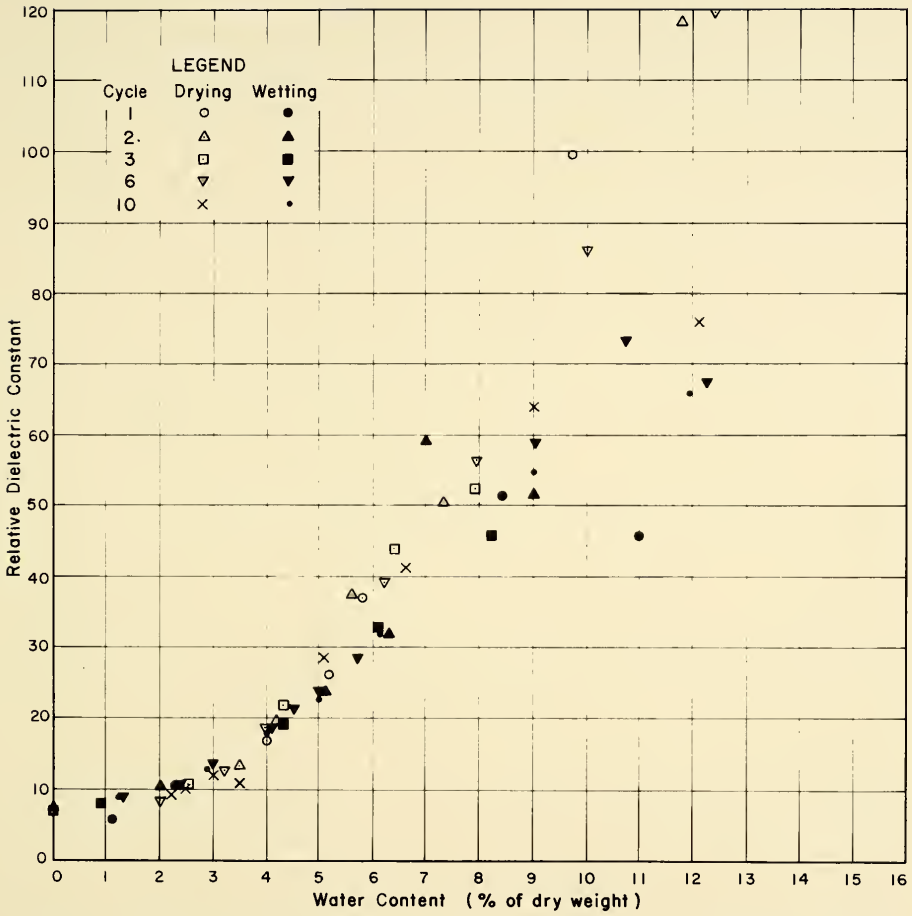

FIG. 37 RELATIVE DIELECTRIC CONSTANT AT 10^6 cps VS. WATER CONTENT FOR DISK MT-1

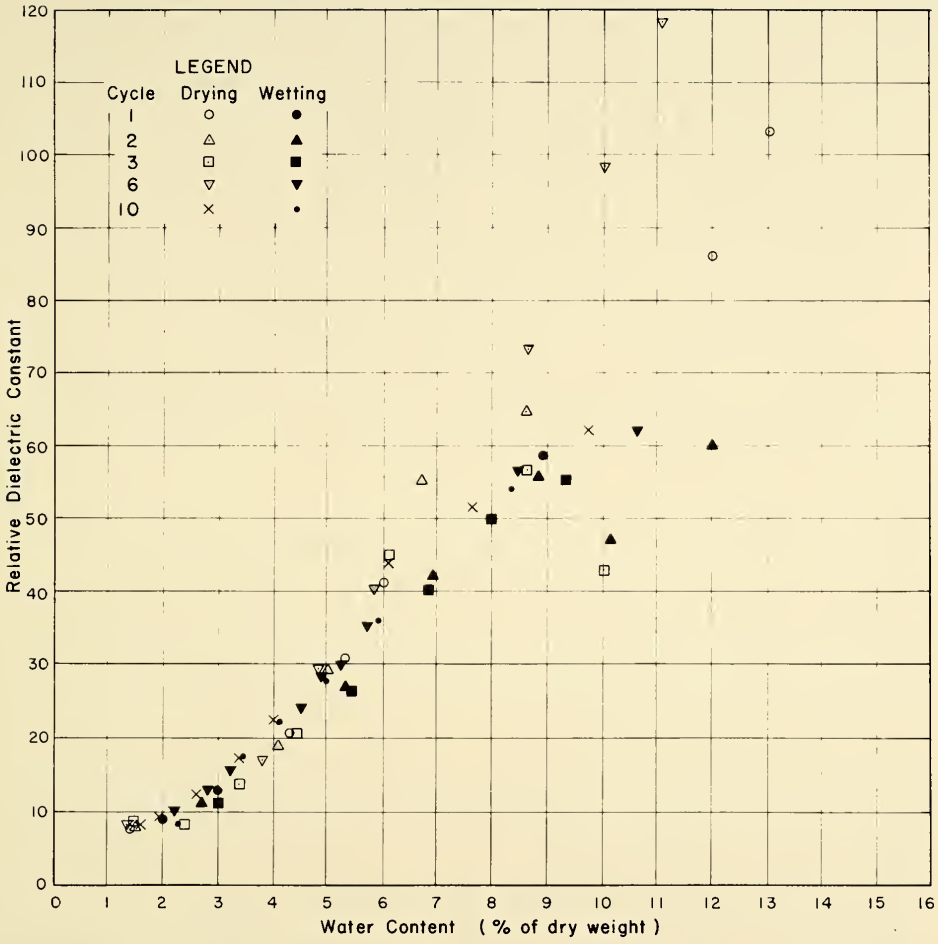

FIG. 38 RELATIVE DIELECTRIC CONSTANT AT 10^6 cps VS. WATER CONTENT FOR DISK MT-2

DISCUSSION OF RESULTS AND SUMMARY

This discussion considers in order the test results in terms of apparent capacitance, 10 cps dielectric conductivity, and 10^6 cps dielectric conductivity and dielectric constant-water content relationships; instrumentation and calibration problems; and finally, the feasibility of using these relationships as moisture indicators. The discussions are centered around the results obtained for the concrete specimens. The trends obtained for the mortar specimens are generally the same as those exhibited by the concrete. Only the numerical values are different.

Test Results

Four conditions were represented by the permittivity tests. Thin disks approximately .4 cm thick and thick disks about .7 cm thick were tested. One of each was dried to 105°C during the test and the others to 60°C. The thin disks dried to 105°C, typified by C-1, exhibited the greatest variation in readings during the ten cycles and the thick disks dried to 60°C, such as CT-2, the least. The thin disks dried to 60°C and the thick disks dried to 105°C were intermediate in this respect.

Certain trends in the apparent capacitance readings for the thin disks dried to 105°C are shown very clearly by the data for disk C-1 on Figure 17. First, there is a marked shifting of the curves with subsequent cycles of drying and wetting. This is most pronounced at the higher water contents where the curves are shifted downward. At the low water contents very little change is noticed, and, if anything, the

capacitance reading increases with subsequent cycles. Second, there is a distinct hysteresis in the drying-wetting cycle. The wetting curve occurs above the drying curve at low water contents but is lower at the higher water contents. Both the hysteresis and shifting of the curves appear to become less pronounced after the sixth cycle.

These trends were exhibited only by the thin samples dried to 105°C. For the other samples the hysteresis remains, but for the thin disks dried to only 60°C and for the thicker disks regardless of their maximum drying temperature, the tendency toward shifting of the curves on subsequent cycles is very weak if it occurs at all.

The shifting of the curves for disk C-1 is as would be predicted from Figure 14 assuming that the resistances of the disks increase with subsequent cycles because of leaching and aging. This same explanation could be used for the hysteresis effect if it were assumed that because the water is held differently in the concrete upon wetting than on drying a higher resistance results during the wetting phase.

When the values of C_b are considered, it becomes apparent that these curves, at least for the water contents above 6 to 8%, are controlled almost completely by the conductances of the disks and their contact capacitances. Considering the thicknesses of disks C-1 and CT-2, the capacitance of disk CT-2 should be about two-thirds that of C-1 for the same water content, assuming dielectric constants approximately equal for equal water contents. However, the curves show that C_b for disk CT-2 is the larger one at the high water contents. This can be the case only if the contact capacitance for CT-2 is the greater of the two and if the resistances of the samples are low enough to make C_b approach this contact

capacitance. This situation is represented by the left-hand edge of Figure 14. Extending the curves on Figures 17 and 18 to estimate their asymptotes, the contact capacitances of disks C-1 and C-2 were estimated to be 300 μμf and 320 μμf respectively. The values of C_b for disk C-1 approach an asymptote at high water contents, especially during the first two cycles and subsequent salt concentration test, and permit a good estimate of the contact capacitance. The thicker disk (CT-2) has a higher resistance and therefore does not approach its asymptote as closely, and its contact capacitance cannot be estimated with the same precision.

The curve for C-1 after salt saturation is much higher than even the first drying cycle and gives additional evidence of the dependency of these values on the conductance of the sample.

For the extreme conditions of drying a thin disk to 105°C and soaking in a 1.0 Normal NaCl solution as represented by disk C-1, the range of water contents at which the same apparent capacitance can be obtained is very wide, being about 5% or more at high water contents and exceeding 1% even at the low water contents. However, for the less severe conditions of 60°C drying and for a thick disk as represented by disk CT-2, the range of water contents at which the same apparent capacitance can be obtained is only about .5% up to water contents of about 6% and then 1 to 1.5% at the highest water contents.

Both the 10 cps dielectric conductivity (Figures 19, 22) and the 10^6 cps dielectric conductivity (Figures 23, 30) show the same general trends as the apparent capacitance curves. The conductivity decreases with successive cycles and exhibits a hysteresis in the cycle for the

samples dried to 105°C. The samples dried to 60°C show less variation between cycles than those dried to 105°C; however, the hysteresis remains essentially unchanged. For the 10^6 cps data the thick samples show less variation than the thin disks. This last comparison cannot be made for the low frequency data as all of these test specimens are approximately the same thickness as the thick disks. Comparing only the results for thick disks with the 10 cps dielectric conductivity data, the 10^6 cps results show less variations than do the low frequency tests (compare Figures 19 and 25 and Figures 20 and 26).

The maximum variation in conductivity at the same water content for these tests is on the order of a factor of 10, which is smaller than that reported by Decoux and Barree (10). The dielectric conductivities at 10^6 cps are higher at low water contents and lower at high water contents than the corresponding 10 cps dielectric conductivities, which is consistent with the results of Keller and Licastro (23) shown on Figure 1. These differences are least at the high water contents, which is also indicated by their data.

The low frequency dielectric conductivity data are consistent and plot as smooth curves with little random scatter in a given drying or wetting phase. This is also true for the greater part of the 10^6 cps data. However, for these latter results there is some random scatter at higher water contents, and disks C-2 and M-2 show some inconsistent trends during the sixth and tenth cycles. These inconsistencies will be discussed later in connection with the discussion of the instrumentation problems.

For the dielectric conductivities calculated from the 10^6 cps

permittivity tests the most severe conditions indicated a maximum range of water contents which could yield the same conductivity value of about 5% or more, which is about the same as the spread for the apparent capacitance data. Also, for the less severe conditions of 60°C drying and no salts added, the spread was only about .5% up to water contents of 6%. The spread in dielectric conductivity as measured by the resistance tests at 10 cps was about twice as great for the conditions of 60°C drying compared with the 10^6 cps data.

The relatively larger variation in the low frequency dielectric conductivity results are not so much the result of shifting of the data with successive cycles of drying and wetting as the result of a larger hysteresis in the cycle. Holmes (18), working with porous sandstone cores, has investigated the influence of allowing evaporation at the surface of the samples during resistance measurements. He found that the distribution of moisture over the cross-section of the core is important and that whether or not evaporation is permitted has a pronounced effect on the resistance measurements. A portion of Holmes' results are shown as Figure 39. In all of his data Holmes found that the curves for cores treated to prevent evaporation at their surface and with uniform moisture distribution had a better approximation to a linear relationship and gave higher resistivity indexes at the same saturation than untreated cores where evaporation was allowed. The results for the 10 cps resistance tests for the sixth cycle on disk RC-2 are shown on Figure 40 plotted as resistivity index versus water-saturation. Resistivity index RI is the ratio of the resistance at a particular water-saturation

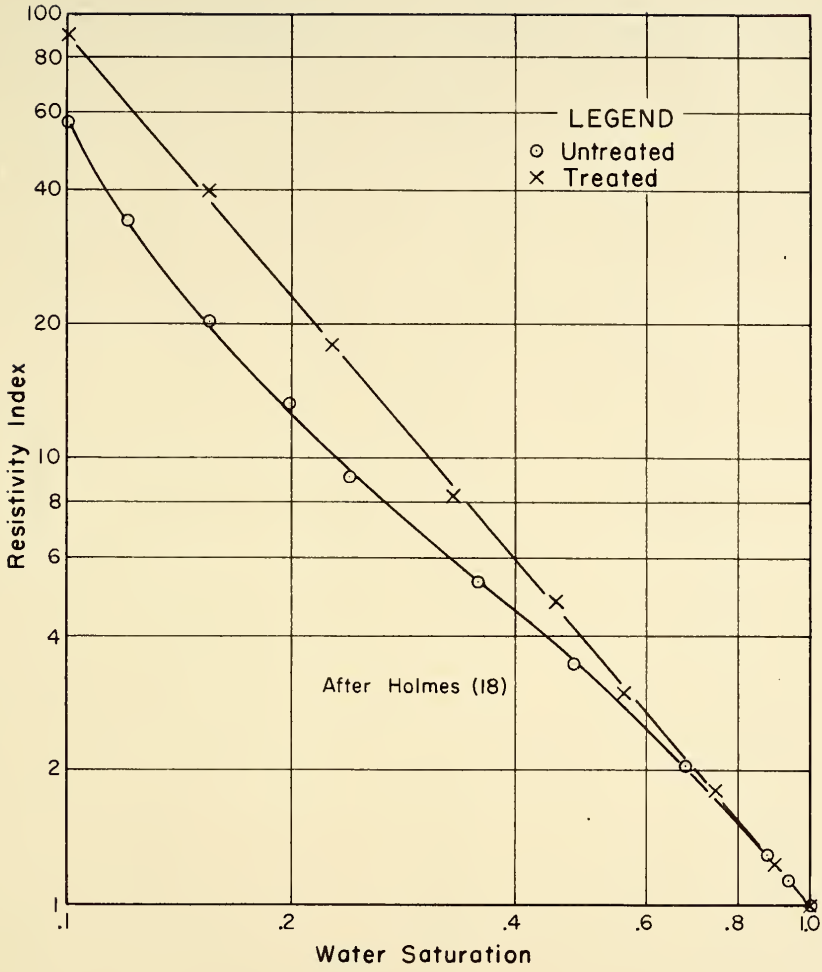

FIG. 39 CURVES OF RESISTIVITY INDEX VS. WATER SATURATION FOR CORE SATURATED WITH A SOLUTION OF 8500 PPM NaCl

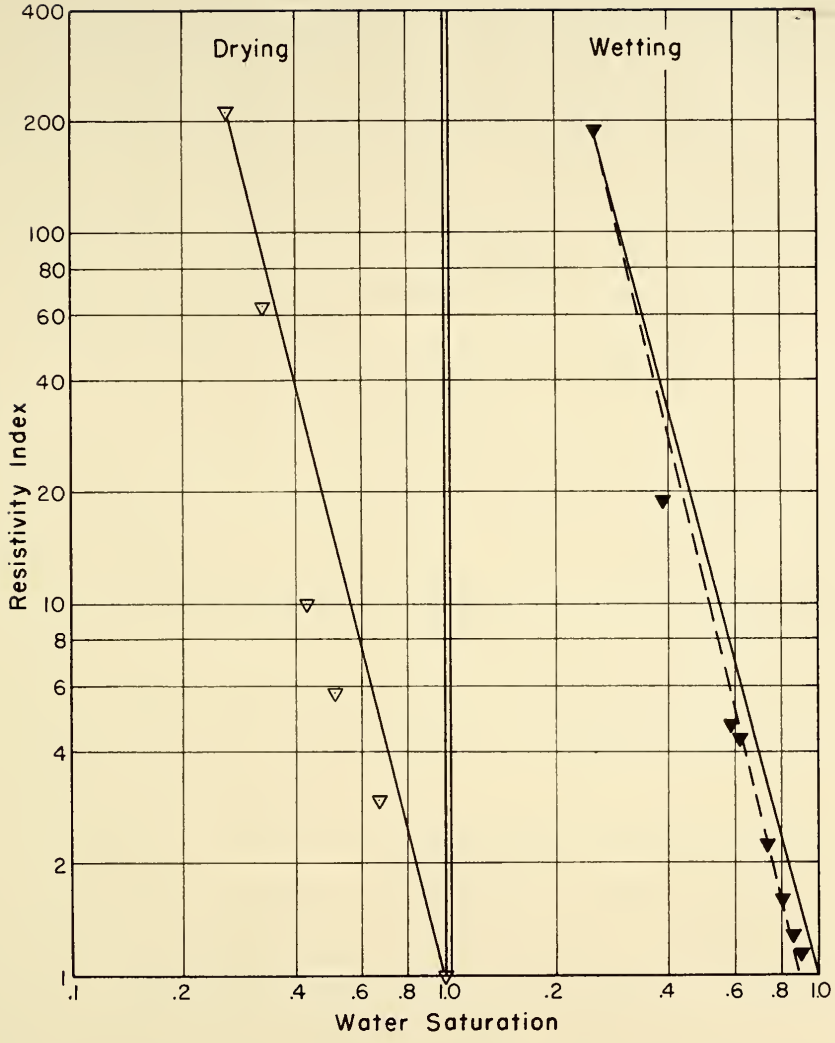

FIG. 40 RESISTIVITY INDEX VS. WATER SATURATION FOR 6th CYCLE OF SAMPLE RC-2

to that at the initial saturation. Both of these curves are plotted relative to their high water content point as the initial condition. The wetting curve is more nearly linear than the drying curve on Figure 40. This suggests that during wetting there is a more uniform moisture distribution in the sample and the wetting data is more truly representative of the conductivity-water content relationship than the drying data which is influenced by the effects of evaporation at the surface of the sample. The wetting curve is even more linear (dashed line, Fig. 40) if it is assumed that at the very high water contents even the points on the wetting cycle are influenced by evaporation.

Evaporation could also be a contributing factor in the hysteresis effect in the permittivity measurements. The effect in the permittivity test should be smaller because of the larger ratio of area to perimeter of these samples and because during testing evaporation is essentially prevented from the faces of the disks by the plates of the capacitance test cell. Holmes' tests indicate that holding the disks in a cell for only two minutes would eliminate much of the evaporation effect for all but the lowest water contents.

The dielectric conductivity data also show the interesting result that, after ten cycles of drying to 60°C, drying the sample to 105°C does not cause any significant shifting of the curves on the subsequent drying after re-wetting with distilled water (see Figures 20 and 24).

The conductivity test results support the contention that the curve shifting and hysteresis effects shown by the apparent capacitant data are largely the results of changes in dielectric conductivity; however, the relative dielectric constant-water content relationships,

(Figures 31-38) as calculated from the 10^6 cps permittivity data show that other factors must also be acting as these curves also show the same trends. The dielectric constant-water content data exhibit the same shifts with successive cycles, the same hysteresis trends, and the same relationships between the magnitude of these variations and the sample size and drying temperature as do the apparent capacitance and conductivity data. The same factors which affect the conductivity are evidently also acting to influence the dielectric constant values. Also, anomalously high dielectric constants are indicated. In nearly all instances values greater than the dielectric constant of bulk water are indicated.

The anomalously high dielectric constants and the variations in the dielectric constant-water content relationship can be rationalized if it is assumed that space-charge or interfacial polarization has an important role in controlling the dielectric constant of concrete. This type of polarization requires the presence of charge carriers free to move under the influence of the applied electric field. In moist concrete these charge carriers could be provided by the ions contained in the pore water. To produce interfacial polarization the charge carriers must be impeded in their motion to cause concentrations of charges which would increase the storage capacity of the capacitor. The solids in the concrete would obstruct the motion of the charge carriers and fulfill this second condition for space-charge polarization. At a given frequency, field strength, and temperature the magnitude of the space charge polarization produced would depend on the ion concentration and the pore structure (pore size, continuity, and tortuosity) and probably the types of ions,--the same factors which are dominant in controlling conductivity. The test results

do not permit any conclusions regarding the relative influences of these various factors. All that can be said is that within the range of conditions employed in the tests those factors which result in net decreases in conductivity also result in decreases in the dielectric constant and vice versa. The large dielectric constants obtained for disk C-1 after soaking in a NaCl solution add further support to the validity of these statements.

At low water contents the relative dielectric constant data are consistent. It is also shown by the flat slope of these curves at the very low water contents that the dielectric constant is relatively insensitive to changes in water content in this range. This may reflect the influence of the surface forces of the cement gel in orienting the water in the gel pores, thereby reducing the dielectric constant of the water to the same order of magnitude as that of the solid matter.

As the water content increases, the random scatter of the relative dielectric constant also increases. This scattering of points makes it difficult to evaluate the true variations in this relationship, but they are at least as great, and possibly greater, than the apparent capacitance and 10^6 cps dielectric conductivity relationships. Soaking in the 1.0 Normal NaCl solution causes relatively greater changes in the dielectric constant than in the other properties, and there are some indications that the change during the first drying is also greater for this property.

Instrumentation and Calibration Problems

The results of the tests in this study give numerous illustrations of the problem encountered in measuring the dielectric properties of concrete in the laboratory and suggest some additional problems which would

be encountered in field measurements.

An important feature of the data obtained is the occasional erratic scatter of some of the data points. This is especially true at the higher water contents and for the dielectric constant results and is due largely to the sensitivity of the calculation procedures to small errors in the test data when the specimen resistance is low. For low values of specimen resistance the curves (Figure 14) are very close together, and a small error in the data can result in picking the wrong value of C_s from this figure. Errors in the test readings can be magnified many times when R_s is very small. At the highest water contents it is sometimes impossible even to approximate the dielectric constant. The dielectric conductivity determinations are also subject to errors for this same reason; however, Figure 14 shows that the resulting error in R_s is not as large as the error in C_s.

Near the left edge of Figure 14 where the C_b- R_s curves approach asymptotically the contact capacitance, if the actual contact capacitance is not equal to the estimated value, very large errors can result. Changes in the contact capacitance during the test are believed to be a cause of unusually low values of dielectric conductivity calculated from the permittivity tests for the sixth and tenth cycles of disks C-2 and M-2. Although much less pronounced, these same anomalous trends are indicated in some of the other 10^6 cps dielectric conductivity data. Too low a value for dielectric conductivity and a correspondingly high dielectric constant value would result if the actual contact capacitance at the time of the test was lower than the contact capacitance value assumed in the calculations. Upon careful inspection of the disks involved,

small crystals were found growing on their faces. This phenomenon was most pronounced on disks C-2 and M-2. When these crystals were scraped off, the curves returned approximately to their expected positions.

As the specimen resistance increases, the sensitivity of the calculations to changes in the contact capacitance is reduced; therefore, it is desirable to proportion the test capacitor to permit working as far to the right on Figure 14 as possible. Unfortunately the control over this factor is limited. From Equation 39

$$C_s = \kappa' C_o \qquad [41]$$

and from Equation 40

$$R_s = \frac{\epsilon_o}{\sigma C_o} \qquad [42]$$

The only factor in these expressions which can be controlled is the geometric capacitance C_o. To increase the specimen resistance the geometric capacitance must be reduced. This also decreases the value of the specimen capacitance reducing the accuracy with which it can be measured. Thus, a compromise in the selection of C_o will be necessary in the design of moisture-measuring equipment.

As R_s is increased, a conflict also developes between the necessity to know the contact capacitance to calculate the dielectric constant and dielectric conductivity and the desirability of working on the more accurate portions of the interpretative graphs. If the specimen resistance is increased sufficiently that the apparent capacitance curve no longer approaches its asymptote, the contact capacitance cannot be accurately estimated. Figures 17 and 18 illustrate this problem. For disk C-1 the asymptote can be estimated fairly well, but for the thicker disk CT-2,

which has a geometric capacitance about one-third smaller than that of C-1, it is difficult to obtain a good estimate of the contact capacitance. It does not appear that any approach adaptable to field use would yield dielectric constant or dielectric conductivity results significantly better than those obtained for the thick disks in this study.

The problems involved with the determination of dielectric constant and dielectric conductivity combined with the smooth curves and relative freedom from erratic scattering of points in the apparent capacitance-water content relationship suggests the possibility of using this relationship as a moisture indicator. This would lead to calibration problems because the apparent capacitance is not a property of the material. It is a function of the complex permittivity of the material, but it is also a function of the contact capacitance and the geometry of the sensing electrodes. Any empirical calibration for the apparent capacitance-water content relationship would have to be accomplished under exactly the same conditions with respect to the contact capacitance and geometric capacitance of the test capacitor as would be experienced in the prototype tests. This would require that calibration be accomplished by embedding sensing elements as nearly identical to those used in the field test as possible in relatively large concrete specimens and calibrating them by varying the water content of these specimens, or the elements would have to be calibrated during the field tests by relating their readings to gravimetric moisture determinations on companion dummy test sections. Both of these approaches would be slow, laborious, and inaccurate.

Indirect calibration techniques could be used to establish the

apparent capacitance-water content relationship. The conductivity and relative dielectric constant-water content relationships could be established by methods similar to those used in this thesis and the apparent capacitance-water content relationship calculated for the sensing capacitors to be used in the field tests. This would require that the contact and geometric capacitance of the sensing capacitor be known. The geometric capacitance could be determined by measurements made with the sensing capacitor immersed in liquids of known dielectric constant. The contact capacitance could be determined similarly using salt water solutions if it is assumed or could be established by test that the electrode to liquid contact capacitance would essentially duplicate the electrode to concrete contact capacitance for elements cast in concrete. If this could not be established, the contact capacitance could be estimated by monitoring the first drying after the element was cast in the concrete and the contact capacitance taken as the asymptote of the C_b-water content curve as was done in this study.

This study has shown that all of the dielectric properties of concrete are sensitive to large increases in the NaCl concentration of the pore water, drying to temperatures significantly above 60°C during the first few cycles, the thickness of the sample tested, and probably by surface evaporation. These factors dictate that if a valid correlation is to be established the calibration tests must be conducted under conditions similar to those for which the correlation is to be used.

The dry weight of concrete increases with age. The magnitude and rate of this increase depends on the environment in which the aging takes place. If corrections are not made for variations in dry weight during

testing the test results will shift successively to the right and indicate much greater variations in the relationships between the dielectric properties and water content than actually occur. The water contents used in all of the relationships studied in this investigation represent the water evaporable at 105°C relative to the 105°C dry weight at the time of the measurement. Some of the random scatter of data points for the samples dried to 60°C may be attributed to difficulties in relating the water contents of these samples to a 105°C dry weight basis.

Evaluation of Electrical Moisture Meters

Considering the basic trends and variations under all conditions tested, there is little to choose between the various properties investigated as moisture indicators. The apparent capacitance, dielectric conductivity (low and high frequency), and relative dielectric constant all exhibit significant variations under certain conditions and none can be used as indicators of water content in concrete under all possible conditions. It is also true, however, that the most serious variations occur only under extreme conditions. Hence, a realistic evaluation can be made only with respect to the conditions under which actual moisture determinations are likely to be made.

In many applications--for example, a concrete pavement slab--the section tested would be relatively massive, would be dried under atmospheric conditions, and, at least in southern climates, would not have salts added to the pore fluid. These conditions would correspond fairly closely to those of the thick samples dried to only 60°C and subject only to leaching. The results for these samples (Figures 18, 20, 26, and 34 for the concrete) show a minimum of variation and shifting of their relationship

with water content on successive cycles of wetting and drying. Also, for many applications the maximum moisture content of interest would not exceed 6 or 8%. For example, it is unlikely that the moisture content of a concrete pavement would normally exceed 8% (36), and in the study of certain properties related to moisture content (such as shrinkage), the moisture range of the greatest importance is less than this value (27). Under such conditions, the dielectric constant, dielectric conductivity, or apparent capacitance as determined from 10^6 cps permittivity measurements could be used successfully as moisture indicators. The indicated accuracy of the determinations would be better than ±.25% for water contents not exceeding 6%.

The indicated accuracy for the dielectric conductivity as determined from low frequency resistance tests is about ±.5% for these same conditions. This is as good as that claimed for supposedly superior methods such as the plaster of Paris or nylon resistance cells (21), but it is only about one-half as good as the 10^6 cps permittivity data; however, as previously discussed, there are indications that the variation in the low frequency conductivity relationships found in these tests may be greater than would be encountered under actual field conditions.

When practical considerations of instrumentation, calibration, and interpretation are considered, the relative advantages and disadvantages of the various relationships as moisture indicators become more apparent. The results of this study permit relative comparisons between five electric moisture-meter schemes as follows:

1. The Capacitance Method.

This method would use the apparent capacitance (C_b)-water content relationship as determined by an empirical calibration. The apparent capacitance in the field would be determined from permittivity measurements on a suitable sensing capacitor embedded in the concrete test section, but the dielectric properties of the concrete would not actually be determined.

2. The Dielectric Constant Method.

This method would utilize the relative dielectric constant-water content relationship established by laboratory tests similar to the permittivity tests used in this study. The relative dielectric constant of the concrete in the field would be calculated from appropriate permittivity tests.

3. The Dielectric Conductivity Method.

This method is identical to the Dielectric Constant Method except that the dielectric conductivity would be calculated from the field permittivity tests.

4. The Complex Permittivity Method.

The apparent capacitance-water content curve would be calculated for the field sensing capacitor from the dielectric constant and dielectric conductivity-water content relationships of the concrete as determined by laboratory calibration tests and a knowledge of the contact and geometric capacitances of the field capacitor. The apparent capacitance of this sensing capacitor embedded in the concrete test section would then be determined from field permittivity tests.

5. The Resistance Method.

This method would use the dielectric conductivity as determined from resistance tests at relatively low frequencies. The calibration could be established by laboratory tests similar to the resistance tests in this study. Field measurements would determine the resistance of a sensing element embedded in the concrete test specimen, and the dielectric conductivity would be calculated from this resistance.

The first four methods are all based on permittivity measurements and require the same instrumentation namely relatively high frequencies and insulated electrodes, and share all of the associated problems with shielding and the contact capacitance. In addition, the contact and geometric capacitances of the sensing element must be predetermined for all but the Capacitance Method.

The Capacitance Method is the same method that has been studied by numerous investigators and reported in the literature. It appears to offer an advantage in the simplicity of calibration and the fact that it does not require extensive data reduction. In actuality, however, calibration is the major disadvantage to this method. Because this is a purely empirical method that depends upon unknown instrumentation factors as well as the properties of the concrete, the calibration must be performed with test capacitors and for conditions identical to those which will be involved in the field tests. This leads to cumbersome and inaccurate calibration procedures.

The difference between the other three permittivity methods

(Methods 2, 3, and 4). is in the methods used to interpret the results. The dielectric constant and dielectric conductivity are calculated from field permittivity measurements and compared with laboratory calibration curves to determine the corresponding water content in the Dielectric Constant and Dielectric Conductivity Methods, respectively. In the Complex Permittivity Method the apparent capacitance is calculated from the field permittivity tests and correlated with an apparent capacitance-water content relationship calculated from laboratory permittivity tests and the characteristics of the field sensing capacitor. The results of this study show that apparent capacitance is less sensitive to small errors in the test data than either dielectric constant or dielectric conductivity. Furthermore, the dielectric constant and dielectric conductivity need only be calculated from laboratory test data which can be more closely controlled than the field tests; erratic scattering of occasional points can readily be identified and neglected in establishing average curves for the dielectric constant and dielectric conductivity-water content relationships. For these reasons, the Complex Permittivity Method is potentially an excellent method of measuring moisture contents in concrete for many possible applications. However, before it can be considered a practical method, the instrumentation required for field measurements must be developed, and the problem of temperature effects must be studied and appropriate corrections developed if required.

The Resistance Method utilizes dielectric conductivity as the moisture indicator. In this respect, it is identical with the dielectric conductivity method. The difference between these methods is the way this property is determined. In the Resistance Method the dielectric

conductivity is determined from resistance measurements instead of permittivity measurements. This is accomplished by designing the instrumentation to make the charging current through the sample small with respect to the loss current. This permits making the measurements at relatively low frequency and with bare electrodes, thereby greatly simplifying both the instrumentation and the necessary calculations. Simplicity is the main advantage of this method. The results of this study show wider variations of the dielectric conductivity-water content relationship as determined by the Resistance Method than from the permittivity relationship, suggesting that the Resistance Method would be less accurate than the Complex Permittivity Method. However, there are indications that this greater variability may not exist under field conditions. As long as this possibility exists, the Resistance Method should not be discarded without further detailed study of all the factors involved.

Summary

The relationships between water content and the dielectric properties of Portland cement concrete and mortar are not constant relationships. They are strongly influenced by the electrical frequency at which they are measured, the salt content of the pore water, and the conditions under which drying and rewetting take place.

The extremes of the variations of these relationships are sufficiently large to make electrical moisture meters unsuitable for all possible environmental conditions. In this study, large variations occurred only when thin specimens were dried to 105°C or where the NaCl concentration of the pore water was increased to 1.0 Normal. When thicker

samples (3-inch disks approximately 1/4 inch thick) were dried to only 60°C and salts were not added, the variations were minor. This is true for at least ten cycles of drying and rewetting with distilled water. For these conditions, permittivity measurements at 10^6 cps are potentially capable of indicating moisture contents in concrete within ±.25% up to water contents of 6 to 8%.

Such accuracies would be adequate for many purposes, and conditions comparable to drying at 60°C and no large increases in salt concentration of the pore water are frequently encountered in practice. However, corrections would have to be made for increases in the dry weight of concrete with aging.

Dielectric conductivity-water content relationships determined by low frequency resistance measurements indicated variations of ±.5% up to water contents of 6 to 8% for the conditions of 60°C maximum temperature and ten cycles of leaching only. There are indications that this greater variation is due, at least partially, to the test conditions and would not occur within a larger test section. Because of the simplicity of this method it should not be discarded until all possibilities for its use have been explored.

The dielectric properties of concrete are potentially accurate indicators of moisture content in concrete for many practical applications and are deserving of further study to develop the necessary instrumentation to permit their use under field conditions. For these methods to be successful, the instrumentation must be very carefully designed for the specific dielectric properties of concrete, due consideration being given to dielectric constant, dielectric conductivity, frequency, and the electrical characteristics of the contact between sensing element and the concrete.

CONCLUSIONS

1. The relationships between the dielectric properties of concrete and water content are not constant. They are influenced by numerous factors other than water content--notably electrical frequency, salt content of the pore fluid, and the environment under which the concrete is aged.

2. The conditions which lead to large variations in the relationships between dielectric properties and water content--such as drying temperatures of 105°C or soaking in 1.0 N salt solutions--are unrealistic with respect to the environments in which moisture determinations would be desired in many practical applications.

3. For moderate environmental conditions, the dielectric properties of concrete as determined from permittivity measurements are potentially capable of indicating the water content of hardened concrete with an accuracy of ±0.25% for moisture content up to 6 or 8%.

4. Low frequency resistance measurements gave an accuracy only half that of the permittivity tests, but there are indications that this accuracy could be improved. Due to the relative simplicity of the instrumentation and of the data reduction involved, this method should not be discarded until its possibilities have been fully explored.

LIST OF REFERENCES

Bibliography

1. _____, "Operating Instructions for Type 716-C Capacitance Bridge with Supplement for Type 716-CS1 Capacitance Bridge," General Radio Company, Concord, Massachusetts (1959).

2. Anderson, A.B.C., "A Method of Determining Soil Moisture Content Based on the Variation of the Electrical Capacitance of Soil at a Low Frequency, with Moisture Content," Soil Science, Vol. 56, pp.29-41 (1943).

3. Balls, W. L., "Capacitance Hygroscopy and Some of its Applications," Nature, Vol. 130, pp. 935-938 (1932).

4. Baherjee, S. S. and Joshi, R. D., "Dielectric Constant and Conductivity of Soil at High Radio Frequencies," Philosophical Magazine, Vol. 25, pp. 1025-1033 (1938).

5. Bell, J. R., "The Feasibility of Measuring Moisture Gradients in Concrete Pavement Slabs," Progress Report No. 2, Joint Highway Research Project, Purdue University (1959).

6. Birch, F. and Schairer, J. F., (editors), "Handbook of Physical Constants," Special Paper No. 36, Geological Society of America, pp. 317-318 (1942)

7. Cashen, G. H., "Measurements of the Electrical Capacity and Conductivity of Soil Blocks," Journal of Agricultural Science, Vol. 22, pp. 145-164 (1932).

8. Childs, E. C., "A Note on Electrical Methods of Measuring Soil Moisture," Soil Science, Vol. 55, pp. 219-223 (1943).

9. Cownie, A. and Palmer, L. S., "The Effect of Moisture on the Electrical Properties of Soil," Proceedings, Vol. 65B, The Physical Society of London, pp. 295-301 (1952).

10. Decoux, R. and Barree, J., "Investigation of the Electrical Conductivity of Concrete" (in French), Circulaire Série F., No. 3, L'Institute Technique du Batiment et des Travaux Publics, Paris (1941).

11. DePlater, C. V., "A Portable Capacitance-Type Soil Moisture Meter," Soil Science, Vol. 80, pp. 391-395 (1955).

12. Dorsey, N. E., "Properties of Ordinary Water-Substances," Reinhold Publishing Corporation, New York (1940).

13. Edlefsen, N. E., "A Review of Results of Dielectric Methods for Measuring Moisture Present in Materials," Agricultural Engineering, Vol. 14, pp. 243-244 (1933).

14. Evjen, H. M., "Theory and Practice of Low-frequency Electromagnetic Exploration," Geophysics, Vol. 13, pp. 584-594 (1948).

15. Field, R. F., "Errors Occurring in the Measurement of Dielectric Constant," Proceedings, Vol. 54, American Society of Testing Materials, pp. 456-478 (1954).

16. Fletcher, J. E., "Dielectric Method for Determining Soil Moisture," Soil Science Society of America Proceedings, Vol. 10, pp. 39-40 (1946).

17. Hammond, E. and Robson, T. D., "Comparison of Electrical Properties of Various Cements and Concretes," The Engineer (London), Vol. 199, pp. 78-80, 114-115 (1955).

18. Holmes, C. R., "Some Factors Related to the Measurement of the Electrical Properties of Porous Sandstone," Eighteenth Technical Conference on Petroleum Production, Bulletin 64, Mineral Industries Experiment Station, The Pennsylvania State University, pp. 37-43 (1954).

19. Howell, Jr. B. F. and Licastro, P. H., "Dielectric Behavior of Rocks and Minerals," The American Mineralogist, Vol. 46, pp. 269-288 (1961).

20. Hasted, J. B., Ritson, D. M., and Collie, C.H., "Dielectric Properties of Aqueous Ionic Solutions, Parts I and II," Journal of Chemical Physics, Vol. 16, pp. 1-21 (1948).

21. Johnson, A. I., "Methods of Measuring Soil Moisture in the Field," Water Supply Paper 1619-U, United States Geological Survey (1962).

22. Jolliffe, C. B., "A Study of Polarization Capacity and Resistance at Radio Frequencies," Physical Review, Vol. 22, pp. 293-302 (1923).

23. Keller, G. V. and Licastro, P. H., "Dielectric Constant and Electrical Resistivity of Natural-State Cores," Bulletin 1052-H, United States Geological Survey (1959).

24. Lill, R. A., Unpublished Personal Correspondence (1958).

25. Marott, A. A. and Smith, E. R., "Table of Dielectric Constants of Pure Liquids," Circular 514, National Bureau of Standards, U. S. Department of Commerce (1951).

26. Maxwell, J. C., "A Treatise on Electricity and Magnetism," 3rd Edition, The Clarendon Press, Oxford (1892).

27. Menzel, C. A., "Method of Determining the Moisture Conditions of Hardened Concrete in Terms of Relative Humidity," Proceedings, Vol. 55, American Society of Testing Materials, pp. 1085-1108 (1955).

28. Powers, T. C., "Causes and Control of Volume Change," Journal of the Research and Development Laboratories, Vol. 1, No. 1, Portland Cement Association, pp. 29-39 (1959).

29. Powers, T. C., Copeland, L. E. and Mann, H. M., "Capillary Continuity or Discontinuity in Cement Pastes," Journal of the Research and Development Laboratories, Vol. 1, No. 2, Portland Cement Association, pp. 38-48 (1959)

30. Powers, T. C., "Some Physical Aspects of the Hydration of Portland Cement," Journal of the Research and Development Laboratories, Vol. 3, No. 1, Portland Cement Association, pp. 47-56 (1961).

31. Sillars, R. W., "The Properties of a Dielectric Containing Semi-Conducting Particles of Various Shapes," Journal, Vol. 80, The Institution of Electrical Engineers, London, pp. 378-394 (1937).

32. Smith-Rose, R. L., "Electrical Properties of Sea-Water for Alternating Currents, Proceedings, Vol. 143A, The Royal Society of London, Vol. 143A, pp. 135-146 (1933).

33. Smyth, C. P., "Dielectric Behavior and Structure," McGraw-Hill Book Company, Inc., New York (1955).

34. Spencer, R. W., "Measurement of the Moisture Content of Concrete," Proceedings, Vol. 34, American Concrete Institute, pp. 45-61 (1938).

35. Steniour, H. H., "Electrical Properties of Concrete," Unpublished interpretation of paper by Hammond and Robson (19), Portland Cement Association (1960).

36. Teller, L. W. and Sutherland, E. C., "The Structural Design of Concrete Pavements," Public Roads, Vol. 16, pp. 169-197 (1935).

37. Von Hippel, A. R., Gross, E.P., Jelatis, J. G. and Geller, M., "Photocurrent, Space Charge Buildup, and Field Emission in Alkalid Halide Crystals," Physical Review, Vol. 91, pp. 568-569 (1953).

38. Von Hippel, A. R., "Dielectrics and Waves," John Wiley and Sons, Inc., New York (1954).

39. Von Hippel, A. R. (editor), "Dielectric Materials and Application," The Technology Press,Massachusetts Institute of Technology and John Wiley and Sons, Inc., New York (1954).

40. Wallihan, E. F., "Studies of the Dielectric Method of Measuring Soil Moisture," Soil Science Society of America Proceedings, Vol. 10, pp. 39-40 (1946).

General References

Dielectrics

National Research Council, "Digest of Literature on Dielectrics," Annual Volumes, National Academy of Sciences (1920-1960).

Brinks, J. B. and Schulman, J. H. (editors), "Progress in Dielectrics," Vol. 2, John Wiley and Sons, Inc., New York (1960).

Brinks, J. B. and Hart, J. (editors), "Progress in Dielectrics," Vol. 3, John Wiley and Sons, Inc., New York (1961).

Brown, W. F., "Dielectrics," Encyclopedia of Physics, Vol. 17, Springer Verlag, Berlin, pp. 1-154 (1956).

Debye, P., "Polar Molecules," The Chemical Catalog Co., Inc., New York (1929).

Fröhlich, H., "Theory of Dielectrics," The Clarendon Press, Oxford, (1949).

Smyth, C. P., "Dielectric Behavior and Structure," McGraw-Hill Book Company, Inc., New York (1955).

Von Hippel, A. R., Dielectrics and Waves," John Wiley and Sons, Inc., New York. (1954).

Electrical Measurements

Campbell, A. and Childs, E. C., "The Measurement of Inductance, Capacitance, and Frequency," The Macmillan Company, New York (1935).

Stout, M. B., "Basic Electrical Measurements," Prentice-Hall, Inc., New York (1950).

Terman, E. T., "Radio Engineers Handbook," McGraw-Hill Book Company, Inc., New York (1943).

Von Hippel, A. R. (editor), "Dielectric Materials and Applications," The Technology Press, Massachusetts Institute of Technology, and John Wiley and Sons, Inc., New York (1954).

Moisture Meters

Highway Research Board, "Bibliography on Methods and Apparatus for Determining Soil Moisture Content," National Academy of Sciences (1950).

Johnson, A. I., "Methods of Measuring Soil Moisture in the Field," Water Supply Paper 1619-U, United States Geological Survey (1962).

Lull, H. W. and Reinhart, K. G., "Soil-Moisture Measurement," Occasional Paper 140, Southern Forest Experiment Station, Forest Service, U. S. Department of Agriculture (1955).

Penner, E., Crawford, C. B., and Eden, W. J., "The Measurement of Moisture Content," Bulletin No. 1, Division of Building Research, National Research Council of Canada, pp. 65-73 (1955).

Shaw, M. D. and Arble, W. C., "Bibliography on Methods of Determining Soil Moisture," Engineering Research Bulletin B-78, College of Engineering and Architecture, Pennsylvania State University (1959).

Concrete

Lea, F. M. and Desch, C. H., "The Chemistry of Cement and Concrete," 2nd Edition Revised by Lea, Edward Arnold, Ltd., London (1956).

Powers, T. C. and Brownyard, T. L., "Studies of the Physical Properties of Hardened Portland Cement Paste," Bulletin 22, Portland Cement Association (1948).

APPENDIX I

Notation

A	area
C	capacitance
C_b	apparent capacitance (parallel equivalent capacitance of combined specimen and contact)
C_c	contact capacitance
C_f	fringe and stray capacitance
C_ℓ	capacitance of leads
C_o	geometric capacitance
C_s	specimen capacitance
C_x	unknown capacitance
C_{xp}	parallel equivalent capacitance of unknown capacitor
C_{xs}	series equivalent capacitance of unknown capacitor
cps	cycles per second
D	dissipation factor = tan δ
D_x	dissipation factor of unknown capacitor
E	applied electric-field strength
E'	local electric-field strength
e	2.718...
G	conductance = 1/R
I	current
I_c	charging current
I_ℓ	loss current
J	current density

J_c	charging current density
J_ℓ	loss current density
j	$\sqrt{-1}$
K	kilohm = 1,000 ohms
L	length
N	number of particles per unit volume
P	polarization
Q	electric charge
R	resistance
R_b	apparent resistance (parallel equivalent resistance of combined specimen and contact)
R_s	parallel equivalent specimen resistance
R_x	unknown resistance
R_{xp}	parallel equivalent resistance of unknown capacitor
R_{xs}	series equivalent resistance of unknown capacitor
RI	resistivity index
S_w	water saturation
t	time
V	instantaneous voltage
V_o	voltage amplitude
w	water content (% of dry weight)
Z	impedance
a	polarizability
α_a	atomic polarizability
α_e	electronic polarizability
α_o	orientation (dipole) polarizability
α_s	space charge (interfacial) polarizability

δ	loss angle
tan δ	loss tangent = D
ϵ_o	dielectric constant of free space (vacuum)
ϵ'	dielectric constant
ϵ''	loss factor
ϵ^*	complex permittivity
θ	power-factor angle
κ'	relative dielectric constant
κ''	relative loss factor
κ^*	complex relative permittivity
μ^*	complex permeability
$\mu\mu f$	unit of capacitance equal to 10^{-12} farads
ν	frequency
σ	dielectric conductivity = $\omega\epsilon''$
ϕ	volume fraction
ω	angular frequency = $2\pi\nu$
°C	degrees Centigrade
°F	degrees Fahrenheit
Ω	ohms

APPENDIX II

Sample Calculations for κ' and σ

The following set of sample calculations of κ' and σ are for the fourth point of the third drying phase for disk CT-2 at a water content of 4.7%. This general range of water content was selected to illustrate the use of the interpretative graphs.

The equipment and sample constants for the disk are

$$C_\ell = 239.2 \ \mu\mu f$$

$$C_f = 9.5 \ \mu\mu f$$

$$C_c = 320.0 \ \mu\mu f$$

$$C_o = 6.0 \ \mu\mu f$$

$$L/A = .0146 \ cm^{-1}$$

$$\omega = 2\pi \times 10^6 = 6.2832 \text{ radians } sec^{-1}$$

The bridge readings for this point were

$$C_{xs} = 438.0 \ \mu\mu f$$

$$D_x = .1676$$

Using Equation 33 to convert the bridge reading to its parallel equivalent

$$C_{xp} = \frac{C_{xs}}{1 + Dx^2} = \frac{438.0}{1 + (.1676)^2} = \underline{426.0 \ \mu\mu f.}$$

Removing the effects of the fringe and lead capacitances with Equations 34 and 35,

$$C_b = C_{xp} - C_\ell - C_f = 426.0 - 239.2 - 9.5 = \underline{177.3 \ \mu\mu f.}$$

$$R_b = \frac{1}{\omega C_{xp} D_x} = \frac{1}{(6.2832)(426.0)(1.676)} = \underline{2,230\ \Omega}.$$

Entering these values of apparent capacitance and resistance on the interpretative graph as shown by the dashed lines on Figure 14 and finding the specimen capacitance which yields the same value of specimen resistance for both relationships,

$$C_s = 260\ \mu\mu f.$$

$$R_s = 550\ \Omega$$

Then from Equation 39 and 41

$$\kappa' = \frac{C_s}{C_o} = \frac{260}{6.0} = 43.3\ .$$

$$\sigma = \frac{L}{AR_s} = \frac{.0146}{530} = 26.5 \times 10^{-6}\ \text{mho cm}^{-1}.$$